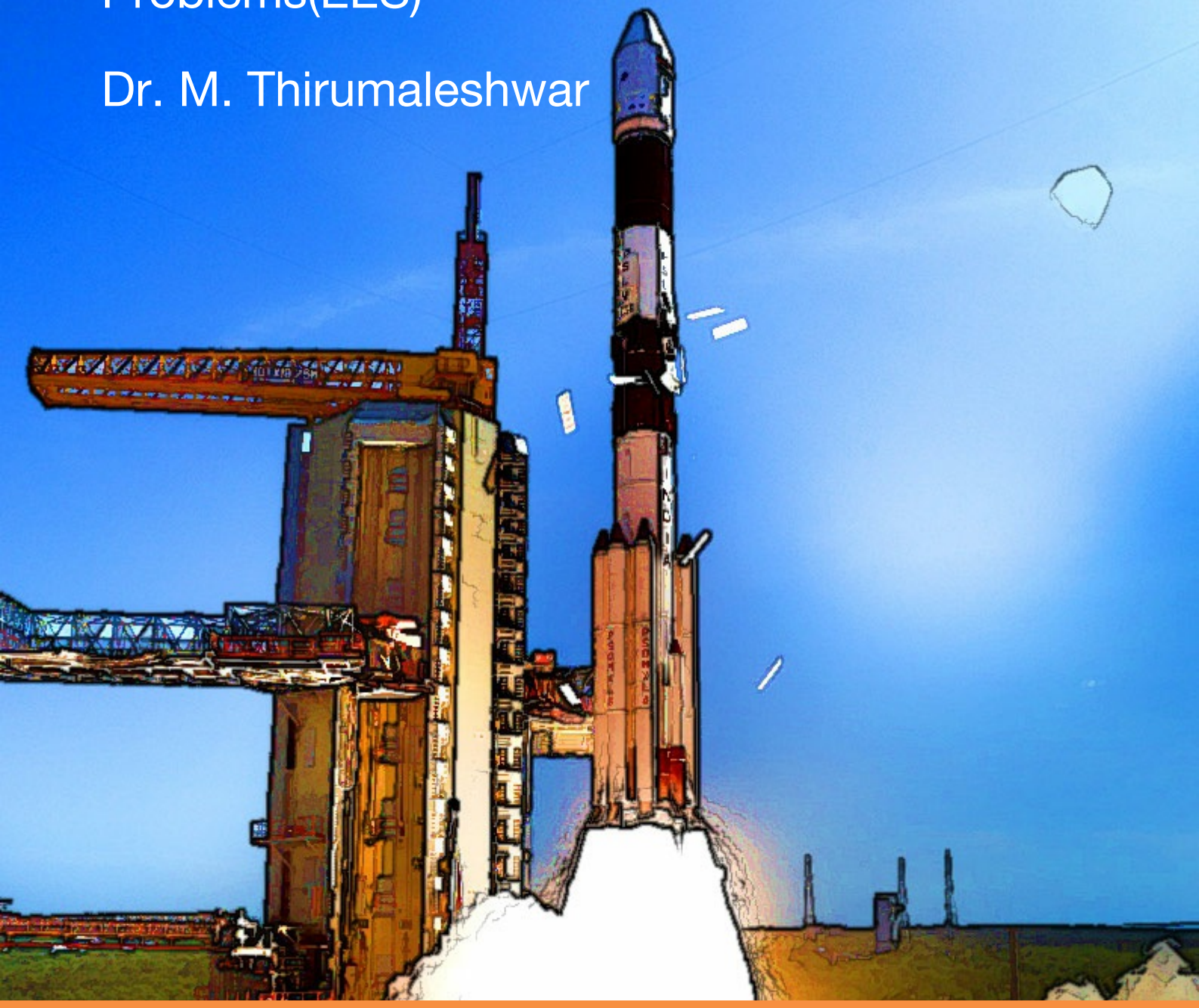
# Cryogenic Engineering: Software Solutions Part-V B

Storage-Insulations-fluid transfer-Problems(EES)

Dr. M. Thirumaleshwar



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# CRYOGENIC ENGINEERING: SOFTWARE SOLUTIONS PART-V B

## STORAGE-INSULATIONS-FLUID TRANSFER-PROBLEMS(EES)

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Cryogenic Engineering: Software Solutions Part-V B: Storage-Insulations-fluid transfer-Problems(EES)
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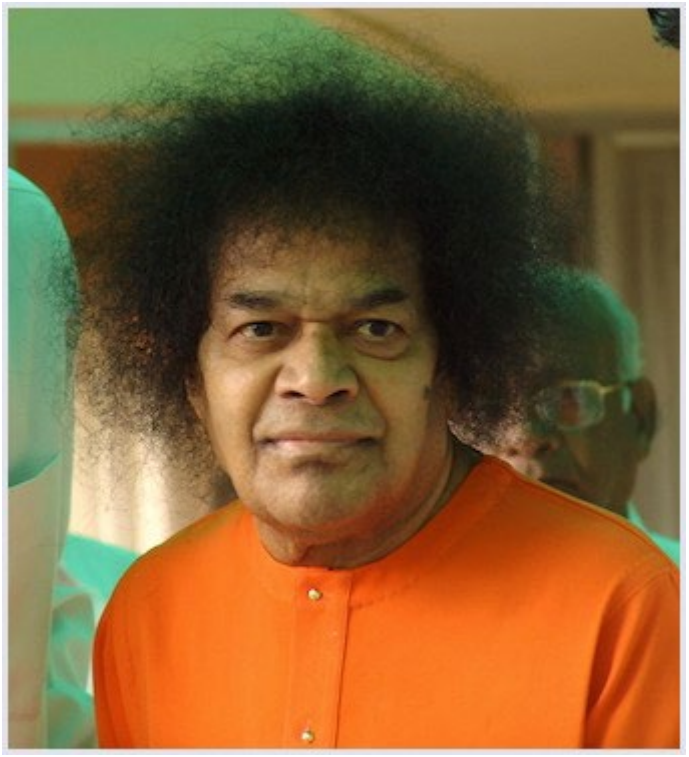
# DEDICATION

**This work is lovingly dedicated at the lotus feet of**

**Bhagavan Sri Sathya Sai Baba**



*"There is only one religion, the religion of Love. There is only one caste, the caste of Humanity. There is only one language, the language of the Heart. There is only one God, He is Omnipresent."*

*"Help Ever, Hurt Never!"*

– ……Bhagavan Sri Sathya Sai Baba

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# IN MEMORIAM....

**Sweetie (13/5/2007 --- 3/10/2019)**

**Our pet, friend and companion, who always remained by my side during writing of all my e-books**

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# PREFACE

This book, viz. **Cryogenic Engineering: Software solutions – Part-V,** is the fifth in the series on **Cryogenic Engineering: Software Solutions.**

This book deals with the topics on **Cryogenic Fluid storage, insulations, and transfer systems.**

**It is being published in two parts: Part- V A and Part- V B.**

**Part-V A contains, essential theory, data and Problems solved in Mathcad.**

**Part-V B contains the essential data, and problems solved with Engineering Equation Solver (EES).**

**This part, i.e. Part-V B,** contains problems solved with Engineering Equation Solver (EES). As with the Part-I, II, III and IV of the series, the focus is on the solutions of problems in Cryogenic engineering using software such as Mathcad and EES. *Only the essential theory and summary of equations required for calculations are given at the beginning of the chapter*.

*Advantages* of using computer software to solve problems are reiterated:

1. It helps in solving the problems fast and accurately
2. Parametric analysis (what – if analysis) and graphical visualization is done very easily. This helps in an in–depth analysis of the problem.
3. Once a particular type of problem is solved, it can be used as a *template* and solving similar problems later becomes extremely easy.
4. In addition, one can plot the data, curve fit, write functions for various properties or calculations and re-use them.
5. These possibilities create interest, curiosity and wonder in the minds of students and enthuse them to know more and work more.

**In this book, following topics are dealt with:**

**Storage vessels, Insulations, and Cryogenic Fluid transfer systems.**

*Under Storage vessels*, we discuss: Design of inner and outer vessels, piping, draining and safety devices

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*Under Insulations,* we cover: Expanded foam, Gas filled powders and fibrous insulations, Vacuum insulation, Evacuated powder and fibrous insulations, Opacified powder insulation, Multilayer insulations. Also, a Table gives comparison of insulations. Important topic of vapor-shielded vessels is also covered.

*Under Cryogenic Fluid transfer systems*, we explain: Vacuum insulated lines, Bayonet joints for lines, cryogenic valves. Two-phase flow in transfer lines and pressure drop calculations and the cool down time and liquid requirements for transfer lines are also dealt with.

**Several Functions are written in Mathcad and EES to simplify the standard and most required calculations. Students, teachers, researchers and professionals may find them very useful**.

Many numerical problems, mostly from the standard Ref.[1], are solved to illustrate the ease of calculations and graphing using Mathcad and EES software.

S. I. Units are used throughout this book. Wide variety of worked examples presented in the book should be useful for those appearing for University, AMIE and Engineering Services examinations.

**Acknowledgements**: Firstly, I would like to **thank all my students**, who have been an inspiration to me in all my academic efforts.

Sincere thanks are due to **Rev. Fr. Joseph Lobo**, Director, St. Joseph Engineering College, Mangalore, for his kindness, regard and words of encouragement.

I am also thankful to **Dr. Thirumaleshwara Bhat**, Principal, Sri Madhwa Vadiraja Institute of Technology and Management, Bantakal, Udupi, for giving me support in my academic activities.

I gratefully remember my former colleagues at the Cryogenics section of Technical Physics Division, Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology, Indore for their sincere cooperation in a true spirit of team-work in all the projects that we undertook.

I particularly salute and admire the vision and foresight of former Heads of Technical Physics Division, BARC viz. late Mr. C. Ambasankaran, Mr. R.Y. Deshpande, Dr. S.R.Gowariker and late Mr. S.S.Ramamurthy in initiating and guiding many of the 'first of its kind' projects for Indian Space Research Organization (ISRO), wherein the Cryogenics section was deeply involved in the design and execution of the projects.

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**I am especially grateful to Prof. R.G.Scurlock, former Director of Institute of Cryogenics, University of Southampton, (U. K.) for writing a message for the Part-I of this series.**

It was indeed gracious of my former Professor, under whom I studied for M.Sc. in Cryogenics at the University of Southampton, U.K. during 1970 – 72, and worked as a Visiting Research Fellow during 1993-94, to honor me by writing this message.

My special thanks to **Bookboon.com** for publishing this *free ebook*. **Ms Karin Jakobsen** and the editorial staff have been most patient and helpful.

Finally, I would like to express my sincere thanks and appreciation to my **wife, Kala,** who, as usual, has given me continuous support, help and encouragement in all my academic activities, making many silent sacrifices.

**M. Thirumaleshwar**

**September, 2019**

**Email:** tmuliya@rediffmail.com

***Note:*** **Along with this book, three ZIP files are also available for free download. They contain 20 'stand alone' EXE files to find properties of cryogenic fluids, design of dewar vessels, material properties, heat transfer through insulations, flow regimes and pressure drop in two phase flow, and cool down time and amount of fluid required in cooling cryogenic lines. They should be of great use for students, teachers and researchers for quick verification of their design calculations.**

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# ABOUT THE AUTHOR

Dr. M. Thirumaleshwar graduated in Mechanical Engineering from Karnataka Regional Engineering College, Surathkal, Karnataka, India, in the year 1965. He obtained M.Sc (cryogenics) from University of Southampton, U.K. and Ph.D.(cryogenics) from Indian Institute of Science, Bangalore, India.

He is a Fellow of Institution of Engineers (India), Life Member, Indian Society for Technical Education, and a Foundation Fellow of Indian Cryogenics Council.

He has worked in India and abroad on large projects in the areas involving heat transfer, fluid flow, vacuum system design, cryo-pumping etc.

He worked as Head of Cryogenics Dept. in Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology (CAT), Indore, from 1966 to 1992.

He worked as Guest Collaborator with Superconducting Super Collider Laboratory of Universities Research Association, in Dallas, USA from 1990 to 1993.

He also worked at the Institute of Cryogenics, Southampton, U.K. as a Visiting Research Fellow from 1993 to 1994.

He was Head of the Dept. of Mechanical Engineering, Fr. Conceicao Rodrigues Institute of Technology, Vashi, Navi Mumbai, India for eight years.

He also worked as Head of Dept. of Mechanical Engineering and Civil Engineering, and then as Principal, Vivekananda College of Engineering and Technology, Puttur (D.K.), India.

**He was Professor and coordinator of Post-graduate program in the Dept. of Mechanical Engineering in St. Joseph Engineering College, Vamanjoor, Mangalore, India.**

A book entitled **"Fundamentals of Heat and Mass Transfer"** authored by him and published by M/s Pearson Education, India (2006) **has been adopted as a Text book** for third year engineering students by the Visweswaraya Technological University (V.T.U.), Belgaum, India.

He has authored a ***free e-book*** entitled **"Software Solutions to Problems on Heat Transfer"** wherein problems are solved using 4 software viz. Mathcad, EES, FEHT and EXCEL. This book, containing about 2750 pages, is presented in 9 parts and all the 9 parts can be downloaded *for free* from www.bookboon.com

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He has also authored ***free e-books*** **on Thermodynamics** entitled **"Basic Thermodynamics: Software Solutions" and "Applied Thermodynamics: Software Solutions"** wherein problems are solved using 3 software viz. Mathcad, EES, and TEST. Each of these titles is presented in 5 parts and all the books can be downloaded *for free* from www.bookboon.com

In addition, he has authored following two useful *free ebooks*:

1. Applied Thermodynamics: Software Solutions: Vapor compression Refrigeration cycle + Problems (Mathcad)
   http://bookboon.com/en/applied-thermodynamics-software-solutions-vapor-ebook
2. Applied Thermodynamics: Software Solutions: Vapor Power cycles (Rankine cycle) + Problems (Mathcad)
   http://bookboon.com/en/applied-thermodynamics-software-solutions-vapor-po-ebook

His earlier *free ebooks in this* **Cryogenic Engineering series**, viz. **Cryogenic Engineering: Software Solutions – Parts-I, II-A and II-B, III-A, III-B and IV** were published by Bookboon recently.

He has also authored **three motivational, free ebooks**, published by www.bookboon.com, entitled as follows:

1. Towards Excellence… How to Study (A Guide book to Students)
2. Towards Excellence… How to teach (A guide book to Teachers)
3. Towards Excellence… Seminars, GD's and Personal Interviews

Dr. M. Thirumaleshwar has attended several National and International conferences and has more than 50 publications to his credit.

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# ABOUT THE SOFTWARE USED

Following software are used while solving problems in this book series:

1. Mathcad 7 and Mathcad 15 (Ref: www.ptc.com)
2. Engineering Equation Solver (EES) (Ref: www.fchart.com), and

For a brief introduction to Mathcad, EES and EXCEL see the chapter 1 of the following *free ebook* by the author:

**"Software Solutions to Problems on Heat Transfer – CONDUCTION-Part-I": http://bookboon.com/en/software-solutions-to-problems-on-heat-transfer-ebook**

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# 6 CRYOGENIC FLUID STORAGE, INSULATIONS, AND TRANSFER SYSTEMS

**Learning objectives**

1. In this chapter, topics on **'Cryogenic Fluid Storage, Insulations, and Transfer systems'** are dealt with.
2. First, essential parts of a dewar vessel are are explained.
3. Next, design of inner and outer vessels are taken up. And, the necessary data tables for design are presented.
4. Several Mathcad Functions are written to quickly determine the required material properties. Mathcad Functions are also written for the design of inner and outer vessels, cylindrical/spherical heads etc. Problems are solved to illustrate the use of these Mathcad Functions.
5. Then, we explain: draining of dewar vessels and pressurization mass requirements, with Mathcad Functions and solved problems.
   And, the various properties of cryogenic fluids required to solve problems in this book are taken from the NIST website, i.e. https://webbook.nist.gov/chemistry/fluid/
6. Various types of insulations used in Cryogenics are discussed next; many Mathcad Functions are written, and problems solved.
7. Vapor-shielded vessels, vacuum insulated transfer lines, bends, thermal strain in lines, bayonet joints, valves etc are explained next. Very useful Mathcad Functions are written for vapor shielded vessels, thermal contraction etc, and many problems solved.
8. Two-phase flow, various flow regimes, and pressure drop in two-phase flow are explained next. Problems are solved to illustrate the Lockhart-Martinelli correlation to determine pressure drop.
9. Next, cool down time for cryogenic lines, amount of cryogenic liquid required to cool down are dealt with, and Mathcad Functions written, and problems solved.
10. Several Functions/ Procedures are written in Mathcad/EES which greatly simplify the calculations. These should be very much useful to teachers, students and researchers working in this field.

==========

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# V-B. PROBLEMS SOLVED WITH ENGINEERING EQUATION SOLVER (EES)

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## PROB.V-B.0

### FIRST, LET US GIVE A FEW DATA TABLES (SEE PART-V A), USEFUL IN SOLVING PROBLEMS:..

**Table 6.1** Allowable Stress for Materials at Room Temperature or Lower

| Material | | Allowable Stress MPa | Allowable Stress psi |
|---|---|---|---|
| Carbon steel (for outer shell only) | SA-285 Grade C | 94.8 | 13,750 |
| | SA-299 | 129.2 | 18,750 |
| | SA-442 Grade 55 | 94.8 | 13,750 |
| | SA-516 Grade 60 | 103.4 | 15,000 |
| Low-alloy steel | SA-202 Grade B | 146.5 | 21,250 |
| | SA-353-B (9% Ni) | 163.7 | 23,750 |
| | SA-203 Grade E | 120.6 | 17,500 |
| | SA-410 | 103.4 | 15,000 |
| Stainless steel | SA-240 (304) | 129.2 | 18,750 |
| | SA-240 (304L) | 120.6 | 17,500 |
| | SA-240 (316) | 129.2 | 18,750 |
| | SA-240 (410) | 112.0 | 16,250 |
| Aluminum | SB-209 (1100-0) | 16.2 | 2,350 |
| | SB-209 (3004-0) | 37.9 | 5,500 |
| | SB-209 (5083-0) | 68.9 | 10,000 |
| | SB-209 (6061-T4) | 41.4 | 6,000 |
| Copper | SB-11 | 46.2 | 6,700 |
| | SB-169 (annealed) | 86.2 | 12,500 |
| Nickel alloys (annealed) | SB-127 (Monel) | 128.2 | 18,600 |
| | SB-168 | 137.9 | 20,000 |

*Source*: ASME Code, Sec. VIII (1983).

**Table 6.2** Weld efficiencies for arc-welded and gas-welded joints (ASME Code, Section VIII, 1983)

| Type of Joint | Fully Radiographed | Spot Examined | Not Spot Examined |
|---|---|---|---|
| Butt joints with complete penetration | 1.00 | 0.85 | 0.70 |
| Single-welded butt joint, backing strip | 0.90 | 0.80 | 0.65 |
| Single-welded butt joint, no backing strip | ... | ... | 0.60 |
| Double full-fillet lap joint | ... | ... | 0.55 |

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**Table 6.3** Geometric characteristics of heads: $D$ = inside diameter, $D_o$ = outside diameter, $t_h$ = thickness, $R$ = dish radius (ASME torispherical)

| Hemispherical | 2:1 Elliptical | ASME Torispherical |
|---|---|---|
| Internal volume<br>$V = \pi D^3/12$ | $V = \pi D^3/24$ | $V = \pi R^3/39.173$ |
| Material volume<br>$V_h = \frac{1}{2}\pi(D + t_h)^2 t_h$ | $V_h = 0.3450\pi(D + t_h)^2 t_h$ | $V_h = 0.264\pi(R + t_h)^2 t_h$ |
| Outside surface area<br>$A_0 = \frac{1}{2}\pi D_o^2$ | $A_0 = 0.3450\pi D_o^2$ | $A_0 = 0.264\pi R^2$ |

The dish radius for the ASME torispherical head is related to the outside diameter of the head as follows: (1) for $D_0 \leqq 42$ in. (1.069 m), $R = D_0 - 2t_h$; (2) for 42 in. $< D_0 <$ 144 in. (3.658 m), $R = D_0 - 2t_h - 6$ in.; (3) for $D_0 \geqq 144$ in., $R = D_0 - 2t_h - 12$ in.

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**Table 6.4** Standard thicknesses for sheet, plate, and heads. Thickness for metric elements is in mm; thickness for conventional elements is in inches.

| Sheet | | Plate | | Heads | |
|---|---|---|---|---|---|
| Metric | Conven. | Metric | Conven. | Metric | Conven. |
| 2.4 | 13 ga. (0.094) | 5 | 3/16 | 5 | 3/16 |
| 2.6 | ... | 6 | 1/4 | 6 | 1/4 |
| 2.8 | 12 ga. (0.109) | 7 | ... | 8 | 5/16 |
| 3.0 | ... | 8 | 5/16 | 10 | 3/8 |
| 3.2 | 11 ga. (0.125) | 9 | ... | 11 | 7/16 |
| 3.4 | ... | 10 | 3/8 | 12 | 1/2 |
| 3.6 | 10 ga. (0.141) | 11 | 7/16 | 14 | 9/16 |
| 3.8 | ... | 12 | 1/2 | 16 | 5/8 |
| 4.0 | ... | 14 | 9/16 | 18 | ... |
| 4.2 | ... | 16 | 5/8 | 20 | 3/4 |
| 4.5 | 8 ga. (0.172) | 18 | ... | 22 | 7/8 |
| 4.8 | ... | 20 | 3/4 | 25 | 1 |
| 5.0 | ... | 22 | 7/8 | 28 | 1 1/8 |
| | | 25 | 1 | 30 | ... |
| | | 28 | 1 1/8 | 32 | 1 1/4 |
| | | 30 | ... | 35 | 1 3/8 |
| | | 32 | 1 1/4 | 38 | 1 1/2 |
| | | 35 | 1 3/8 | 40 | 1 5/8 |
| | | 38 | 1 1/2 | 45 | 1 3/4 |
| | | 40 | 1 5/8 | 50 | 2 |
| | | 45 | 1 3/4 | | |
| | | 50 | 2 | | |

**Table 6.5** Typical mechanical properties of metals

| Metal | Density | | Young's Modulus | | Poisson's Ratio |
|---|---|---|---|---|---|
| | $kg/m^3$ | $lb_m/in^3$ | GPa | psi | |
| Carbon steel | 7720 | 0.279 | 200 | $29 \times 10^6$ | 0.27 |
| Low-alloy steel | 7830 | 0.283 | 200 | $29 \times 10^6$ | 0.27 |
| Stainless steel | 7920 | 0.286 | 207 | $30 \times 10^6$ | 0.28 |
| Aluminum | 2700 | 0.098 | 69 | $10 \times 10^6$ | 0.33 |
| Copper | 8940 | 0.323 | 117 | $17 \times 10^6$ | 0.33 |
| Monel | 8830 | 0.319 | 179 | $26 \times 10^6$ | 0.32 |

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**Table 6.6** Equivalent radius for elliptical heads under external pressure. $R_0 = K_1 D$ and $D$ = major diameter of the ellipse, $D_1$ = minor diameter of the ellipse.

| $D/D_1$ | $K_1$ | $D/D_1$ | $K_1$ |
|---|---|---|---|
| 3.0 | 1.36 | 1.8 | 0.81 |
| 2.8 | 1.27 | 1.6 | 0.73 |
| 2.6 | 1.18 | 1.4 | 0.65 |
| 2.4 | 1.08 | 1.2 | 0.57 |
| 2.2 | 0.99 | 1.0 | 0.50 |
| 2.0 | 0.90 | | |

**Thermal conductivities of materials, k_t,( W/m.K) --Ref: Barron.**

| Temp. (K) | BeCu | AL 6063-T5 | Steel1020 | SS 304 | Monel | Teflon |
|---|---|---|---|---|---|---|
| 4 | 1.9 | 34 | 3 | 0.24 | 0.43 | 0.046 |
| 10 | 4.8 | 86 | 11.5 | 0.77 | 1.74 | 0.096 |
| 20 | 10.6 | 170 | 24 | 1.95 | 4.3 | 0.141 |
| 30 | 16.2 | 230 | 32 | 3.3 | 6.9 | 0.174 |
| 40 | 21 | 270 | 38.6 | 4.7 | 9 | 0.193 |
| 50 | 26.1 | 280 | 47.6 | 5.8 | 10.95 | 0.208 |
| 60 | 30 | 270 | 53.6 | 6.8 | 12.09 | 0.219 |
| 70 | 33.7 | 248 | 57.5 | 7.6 | 13.06 | 0.228 |
| 80 | 37 | 230 | 60 | 8.26 | 13.9 | 0.235 |
| 90 | 40.1 | 222 | 61.8 | 8.86 | 14.63 | 0.241 |
| 100 | 43 | 216 | 62.9 | 9.4 | 15.27 | 0.245 |
| 120 | 48.4 | 207 | 64.1 | 10.36 | 16.26 | 0.251 |
| 140 | 53.3 | 201 | 64.6 | 11.17 | 17.34 | 0.255 |
| 160 | 57.6 | 200 | 64.8 | 11.86 | 18.25 | 0.257 |
| 180 | 61.5 | 200 | 64.9 | 12.47 | 19.02 | 0.258 |
| 200 | 65 | 200 | 65 | 13 | 19.69 | 0.259 |
| 250 | 72.4 | 200 | 65 | 14.07 | 21.02 | 0.26 |
| 300 | 78.5 | 200 | 65 | 14.9 | 22 | 0.26 |

**Table 6.7** A. Thermal conductivity of materials[1]

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| Th. Cond. Integrals, K, from 300K to 4K, (W/m) (Ref: Barron): | | | | | | |
|---|---|---|---|---|---|---|
| Temp. (K) | BeCu | AL 6063-T5 | Steel1020 | SS 304 | Monel | Teflon |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 19 | 360 | 43 | 2.9 | 6.3 | 0.44 |
| 20 | 95 | 1650 | 222 | 16.3 | 36.4 | 1.64 |
| 30 | 229 | 3650 | 502 | 42.4 | 92.9 | 3.23 |
| 40 | 415 | 6200 | 867 | 82.4 | 173 | 5.08 |
| 50 | 650 | 8950 | 1310 | 135 | 273 | 7.16 |
| 60 | 930 | 11700 | 1810 | 198 | 368 | 9.36 |
| 70 | 1250 | 14300 | 2360 | 270 | 513 | 11.6 |
| 80 | 1600 | 16700 | 2950 | 349 | 647 | 13.9 |
| 90 | 1990 | 19000 | 3550 | 436 | 791 | 16.3 |
| 100 | 2400 | 21100 | 4170 | 528 | 940 | 18.7 |
| 120 | 3300 | 25300 | 5450 | 726 | 1260 | 23.7 |
| 140 | 4320 | 29300 | 6750 | 939 | 1590 | 28.7 |
| 160 | 5440 | 33300 | 8050 | 1170 | 1950 | 33.8 |
| 180 | 6640 | 37300 | 9350 | 1410 | 2320 | 39 |
| 200 | 7910 | 41300 | 10700 | 1660 | 2710 | 44.2 |
| 250 | 11300 | 51300 | 13900 | 2340 | 3730 | 57.2 |
| 300 | 15000 | 61300 | 17200 | 3060 | 4800 | 70.2 |

**Table 6.7** B. Thermal conductivity Integrals.[1]

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| Thermal expansion of materials: Ref: Barron | | | | |
|---|---|---|---|---|
| | BeCu | Alumimium | 1020Steel | SS304 |
| T(K) | (ΔL/L)* 10^5 | (ΔL/L)* 10^5 | (ΔL/L)* 10^5 | (ΔL/L)* 10^5 |
| 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 0 | 0 |
| 40 | 1 | 2 | 1 | 0 |
| 50 | 3 | 5 | 2 | 2 |
| 60 | 7 | 10 | 4 | 5 |
| 70 | 12 | 16 | 7 | 11 |
| 80 | 20 | 24 | 10 | 17 |
| 90 | 29 | 34 | 15 | 25 |
| 100 | 39 | 45 | 20 | 35 |
| 120 | 61 | 72 | 32 | 55 |
| 140 | 85 | 103 | 47 | 78 |
| 160 | 110 | 138 | 64 | 103 |
| 180 | 137 | 175 | 82 | 129 |
| 200 | 165 | 214 | 101 | 157 |
| 250 | 242 | 318 | 155 | 229 |
| 300 | 329 | 431 | 210 | 307 |

**Table 6.7** C. Thermal expansion of materials[1]

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**contd…**

| T(K) | Monel (ΔL/L)* 10^5 | Invar (ΔL/L)* 10^5 | Teflon (ΔL/L)* 10^5 | Pyrex (ΔL/L)* 10^5 | Nylon (ΔL/L)* 10^5 | Polystyrene (ΔL/L)* 10^5 |
|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 20 | 0 | 0 | 30 | -1 | 10 | 28 |
| 40 | 1 | 0 | 80 | -2 | 37 | 84 |
| 50 | 3 | 0 | 109 | -1.9 | 58 | 118 |
| 60 | 6 | 0 | 140 | -1.5 | 81 | 156 |
| 70 | 10 | 1 | 176 | -0.6 | 110 | 196 |
| 80 | 15 | 2 | 210 | 1 | 142 | 242 |
| 90 | 21 | 3 | 250 | 2.8 | 177 | 286 |
| 100 | 26 | 5 | 290 | 4.5 | 217 | 339 |
| 120 | 45 | 9 | 380 | 8.5 | 301 | 445 |
| 140 | 64 | 13 | 480 | 13 | 393 | 558 |
| 160 | 84 | 18 | 600 | 17.5 | 493 | 676 |
| 180 | 107 | 23 | 740 | 22.5 | 600 | 798 |
| 200 | 130 | 29 | 900 | 27.5 | 716 | 924 |
| 250 | 193 | 41 | 1390 | 41.7 | 1050 | 1250 |
| 300 | 261 | 54 | 1600 | 57 | 1450 | 1601 |

**Table 6.8** Stainless-steel IPS pipe sizes

| Nominal Size (in.) | OD (in.) | Wall Thickness (in.) | | | |
|---|---|---|---|---|---|
| | | Schedule 5 | Schedule 10 | Schedule 40 | Schedule 80 |
| ½ | 0.840 | 0.065 | 0.083 | 0.109 | 0.147 |
| ¾ | 1.050 | 0.065 | 0.083 | 0.113 | 0.154 |
| 1 | 1.315 | 0.065 | 0.109 | 0.133 | 0.179 |
| 1¼ | 1.660 | 0.065 | 0.109 | 0.140 | 0.191 |
| 1½ | 1.900 | 0.065 | 0.109 | 0.145 | 0.200 |
| 2 | 2.375 | 0.065 | 0.109 | 0.154 | 0.218 |
| 2½ | 2.875 | 0.083 | 0.120 | 0.203 | 0.276 |
| 3 | 3.500 | 0.083 | 0.120 | 0.216 | 0.300 |
| 3½ | 4.000 | 0.083 | 0.120 | 0.226 | 0.318 |
| 4 | 4.500 | 0.083 | 0.120 | 0.237 | 0.337 |
| 5 | 5.563 | 0.109 | 0.134 | 0.258 | 0.375 |
| 6 | 6.625 | 0.109 | 0.134 | 0.280 | 0.432 |
| 8 | 8.625 | 0.109 | 0.148 | 0.322 | 0.500 |
| 10 | 10.750 | 0.134 | 0.165 | 0.365 | 0.500 |
| 12 | 12.750 | 0.156 | 0.180 | 0.375 | 0.500 |
| 14 | 14.000 | 0.156 | 0.188 | 0.375 | 0.500 |
| 16 | 16.000 | 0.165 | 0.188 | 0.375 | 0.500 |
| 18 | 18.000 | 0.165 | 0.188 | 0.375 | 0.500 |
| 20 | 20.000 | 0.188 | 0.218 | 0.375 | 0.500 |
| 22 | 22.000 | 0.188 | 0.218 | 0.375 | 0.500 |
| 24 | 24.000 | 0.218 | 0.250 | 0.375 | 0.500 |

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**Table 6.9** Stainless-steel IPS pipe sizes (metric)

| Nominal Size (mm) | OD (mm) | Wall Thickness (mm) | | | |
|---|---|---|---|---|---|
| | | Schedule 5 | Schedule 10 | Schedule 40 | Schedule 80 |
| 15 | 21.3 | 1.7 | 2.1 | 2.8 | 3.7 |
| 20 | 26.7 | 1.7 | 2.1 | 2.9 | 3.9 |
| 25 | 33.4 | 1.7 | 2.8 | 3.4 | 4.6 |
| 32 | 42.2 | 1.7 | 2.8 | 3.6 | 4.9 |
| 40 | 48.3 | 1.7 | 2.8 | 3.7 | 5.1 |
| 50 | 60.3 | 1.7 | 2.8 | 3.9 | 5.5 |
| 65 | 73.0 | 2.1 | 3.1 | 5.2 | 7.0 |
| 80 | 101.6 | 2.1 | 3.1 | 5.7 | 8.1 |
| 100 | 114.3 | 2.1 | 3.1 | 6.0 | 8.6 |
| 125 | 141.3 | 2.8 | 3.4 | 6.6 | 9.5 |
| 150 | 168.3 | 2.8 | 3.4 | 7.1 | 11.0 |
| 200 | 219.1 | 2.8 | 3.8 | 8.2 | 12.7 |
| 250 | 273.1 | 3.4 | 4.2 | 9.3 | 12.7 |
| 300 | 323.9 | 4.0 | 4.6 | 9.5 | 12.7 |
| 350 | 355.6 | 4.0 | 4.8 | 9.5 | 12.7 |
| 400 | 406.4 | 4.2 | 4.8 | 9.5 | 12.7 |
| 450 | 457.2 | 4.2 | 4.8 | 9.5 | 12.7 |
| 500 | 508.0 | 4.8 | 5.5 | 9.5 | 12.7 |
| 550 | 558.8 | 4.8 | 5.5 | 9.5 | 12.7 |
| 600 | 609.6 | 5.5 | 6.4 | 9.5 | 12.7 |

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**Another useful extract from a chart to determine the wall thickness of a pipe is given below:**

**Ref: https://www.nandishwarsteel.com/pdf/pipes-new.pdf**

**STAINLESS STEEL PIPE DIMENSION AS PER ASTM & WEIGHT-KG. PER MTR. (ANSI B36.19)**

| Nominal Bore | | Outside Diameter | Sch-5S | | Sch-10S | | Sch-40S | | Sch-80S | | Sch-160S | | Sch-XXS | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mm | INCH | mm | Wt mm | Weight (Kg/mt) | Wt mm | Weight (Kg/mt) | Wt mm | Weight (Kg/mt) | Wt mm | Weight (Kg/mt) | Wt mm | Weight (Kg/mt) | Wt mm | Weight (Kg/mt) |
| 3 | 1/8 | 10.3 | 1.24 | 0.276 | 1.24 | 0.28 | 1.73 | 0.37 | 2.41 | 0.47 | - | - | - | - |
| 6 | 1/4 | 13.7 | 1.24 | 0.390 | 1.65 | 0.49 | 2.24 | 0.631 | 3.02 | 0.80 | - | - | - | - |
| 10 | 3/8 | 17.1 | 1.24 | 0.490 | 1.65 | 0.63 | 2.31 | 0.845 | 3.20 | 1.10 | - | - | - | - |
| 15 | 1/2 | 21.3 | 1.65 | 0.800 | 2.11 | 1.00 | 2.77 | 1.27 | 3.75 | 1.62 | 4.75 | 1.94 | 7.47 | 2.55 |
| 20 | 3/4 | 26.7 | 1.65 | 1.03 | 2.11 | 1.28 | 2.87 | 1.68 | 3.91 | 2.20 | 5.54 | 2.89 | 7.82 | 3.63 |
| 25 | 1 | 33.4 | 1.65 | 1.30 | 2.77 | 2.09 | 3.38 | 2.50 | 4.55 | 3.24 | 6.35 | 4.24 | 9.09 | 5.45 |
| 32 | 1 1/4 | 42.2 | 1.65 | 1.65 | 2.77 | 2.70 | 3.56 | 3.38 | 4.85 | 4.47 | 6.35 | 5.61 | 9.70 | 7.77 |
| 40 | 1 1/2 | 48.3 | 1.65 | 1.91 | 2.77 | 3.11 | 3.68 | 4.05 | 5.08 | 5.41 | 7.14 | 7.25 | 10.16 | 9.54 |
| 50 | 2 | 60.3 | 1.65 | 2.40 | 2.77 | 3.93 | 3.91 | 5.44 | 5.54 | 7.48 | 8.74 | 11.1 | 11.07 | 13.44 |
| 65 | 2 1/2 | 73.0 | 2.11 | 3.69 | 3.05 | 5.26 | 5.16 | 8.63 | 7.01 | 11.4 | 9.53 | 14.9 | 14.2 | 20.39 |
| 80 | 3 | 88.9 | 2.11 | 4.51 | 3.05 | 6.45 | 5.49 | 11.30 | 7.62 | 15.2 | 11.1 | 21.3 | 15.24 | 27.65 |
| 100 | 4 | 114.3 | 2.11 | 5.84 | 3.05 | 8.36 | 6.02 | 16.07 | 8.56 | 22.3 | 13.49 | 33.54 | 17.12 | 41.03 |
| 125 | 5 | 141.3 | 2.77 | 9.47 | 3.40 | 11.57 | 6.55 | 21.8 | 9.53 | 31.97 | 15.88 | 49.11 | 19.05 | 57.43 |
| 150 | 6 | 168.3 | 2.77 | 11.32 | 3.40 | 13.84 | 7.11 | 28.3 | 10.97 | 42.7 | 18.2 | 67.56 | 21.95 | 79.22 |
| 200 | 8 | 219.1 | 2.77 | 14.79 | 3.76 | 19.96 | 8.18 | 42.6 | 12.7 | 64.6 | 23.0 | 111.2 | 22.23 | 107.8 |
| 250 | 10 | 273.1 | 3.40 | 22.63 | 4.19 | 27.78 | 9.27 | 60.5 | 12.7 | 96.0 | 28.6 | 172.4 | 25.40 | 155.15 |
| 300 | 12 | 323.9 | 3.96 | 31.25 | 4.57 | 36.00 | 9.52 | 73.88 | 12.7 | 132.0 | 33.32 | 238.76 | 25.40 | 186.97 |
| 350 | 14 | 355.6 | 3.96 | 34.36 | 4.78 | 41.3 | 11.13 | 94.59 | 19.05 | 158.08 | 35.71 | 281.70 | - | - |
| 400 | 16 | 406.4 | 4.19 | 41.56 | 4.78 | 47.29 | 12.7 | 123.30 | 21.41 | 203.33 | 40.46 | 365.11 | - | - |
| 450 | 18 | 457.2 | 4.19 | 46.80 | 4.78 | 53.42 | 14.27 | 155.80 | 23.8 | 254.36 | 45.71 | 466.40 | - | - |
| 500 | 20 | 508.0 | 4.78 | 59.25 | 5.54 | 68.71 | 15.09 | 183.42 | 26.19 | 311.2 | 49.99 | 564.68 | - | - |
| 600 | 24 | 609.6 | 5.54 | 82.47 | 6.35 | 94.45 | 17.48 | 255.41 | 30.96 | 442.08 | 59.54 | 808.22 | - | - |

## PROB.V-B.1

### WRITE EES PROCEDURES FOR GEOMETRICAL CHARACTERISTICS OF HEADS:

D = inside dia, $D_0$ = outside dia, th = thickness, R = dish radius (ASME torisph.)
Take formulas from Table 6.3.

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**EES Procedure is given below:**

```
$UNITS SI kg m kPa K

PROCEDURE Hemisph_head( D, D_o, t_h : V, V_h, A_o)

"Hemispherical head properties... from Table in Barron..

Inputs: D = inside dia; D_o = outside dia, t_h = thickness;"

"Outputs: V = internal volume; V_h = material volume; A_o = outside surface area "

V = pi * D^3 / 12

V_h = (pi / 2) * (D + t_h)^2 * t_h

A_o = (1/ 2) * pi * D_o^2

END

"================================================================"

"Example:"

D = 3.05 "m"

D_o = 3.07 "m"

t_h = 0.01 "m"

CALL  Hemisph_head( D, D_o, t_h : V, V_h, A_o)
```

**Results:**

**Unit Settings: SI K kPa kJ mass deg**

$A_o$ = 14.8 [m$^2$] $D$ = 3.05 [m] $D_o$ = 3.07 [m] $t_h$ = 0.01 [m] $V$ = 7.428 [m$^3$]
$V_h$ = 0.1471 [m$^3$]

PROCEDURE Elliptical_head( D, D_o, t_h : V, V_h, A_o)

"2:1 Elliptical head properties... from Table in Barron..

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Inputs: D = inside dia; D_o = outside dia, t_h = thickness;"

"Outputs: V = internal volume; V_h = material volume; A_o = outside surface area "

V = pi * D^3 / 24

V_h = 0.3450 * pi * (D + t_h)^2 * t_h

A_o =0.3450 * pi * D_o^2

END

"============================================================="

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"Example:"

D = 3.05 "m"

D_o = 3.07 "m"

t_h = 0.01 "m"

CALL Elliptical_head( D, D_o, t_h : V, V_h, A_o)

**Results:**

**Unit Settings: SI K kPa kJ mass deg**

$A_o$ = 10.22 [$m^2$] D = 3.05 [m] $D_o$ = 3.07 [m] $t_h$ = 0.01 [m] V = 3.714 [$m^3$]

$V_h$ = 0.1015 [$m^3$]

---

PROCEDURE ASME_Torisph_head(R, t_h : V, V_h, A_o)

"ASME Torispherical head properties... from Table in Barron..

Inputs:R = dish radius; t_h = thickness;"

"Outputs: V = internal volume; V_h = material volume; A_o = outside surface area "

V = pi * R^3 / 39.173

V_h = 0.264 * pi * ( R + t_h)^2 * t_h

A_o = 0.264 * pi * R^2

END

"============================================================="

"Example:"

R = 1.502 "m"

t_h = 0.01 "m"

CALL ASME_Torisph_head(R, t_h : V, V_h, A_o)

"========================================================"

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**Results:**

Unit Settings: SI K kPa kJ mass deg

$A_o = 1.871$ [m$^2$] $R = 1.502$ [m] $t_h = 0.01$ [m] $V = 0.2718$ [m$^3$] $V_h = 0.01896$ [m$^3$]

"========================================================"

## PROB.V-B.2

### WRITE AN EES FUNCTION FOR MIN. THICKNESS OF INNER SHELL FOR A CYLINDRICAL VESSEL SURROUNDED BY A VACUUM JACKET.

We have, from Ref.[1]:

$$t_{shell} = \frac{p \cdot D}{2 \cdot S_a \cdot e_w - 1.2 \cdot p} = \frac{p \cdot D_0}{2 \cdot S_a \cdot e_w + 0.8 \cdot p} \quad \text{...mm}$$

where:

p = design internal pressure (abs. pressure for vac. jacketed vessels), kPa

D = inside dia of shell, mm

$D_0$ = OD of shell, mm

$S_a$ = allowable stress, kPa

$e_w$ = weld effcy.

**The EES Function (based on inside dia of shell):**

---

FUNCTION t_inner_shell(p, D, S_a, e_w)

"EES function for min. thickness of inner shell for a cylindrical vessel surrounded by a vacuum jacket.

Based on inner dia of shell.

Inputs: p = design internal pressure, kPa; D = ID of shell,m m; S_a = allowable pressure, kPa; e_w = weld efficiency

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Output: thickness of shell, mm, “

t_inner_shell = (p * D) / (2 * S_a * e_w - 1.2 * p)

END

```
"================================================================"

 "Example:"

 p = 800 "kPa"

 D = 3050 "mm"

 S_a = 129200 "kPa"

 e_w = 1

 "Then, we get:"

 t_h = t_inner_shell(p, D, S_a, e_w)

 "================================================="
```

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**Results:**

Unit Settings: SI K kPa kJ mass deg

$D = 3050$ [mm] $e_w = 1$ $p = 800$ [kPa] $S_a = 129200$ [kPa] $t_h = 9.478$ [mm]

**Thus: t_h = 9.478 mm …Ans.**

"========================================================"

## PROB.V-B.3

### WRITE AN EES FUNCTION FOR MIN. THICKNESS FOR SPHERICAL SHELLS, HEMISPH. HEADS, ELLIPTICAL HEADS, OR ASME TORISPHERICAL HEADS:

We have, from Ref. [1],

$$t_h = \frac{p \cdot D \cdot K}{2 \cdot S_a \cdot e_w - 0.2 \cdot p} = \frac{p \cdot D_0 \cdot K}{2 \cdot S_a \cdot e_w + 2 \cdot p \cdot (K - 0.1)} \quad \text{...mm}$$

where:

D = inside dia of spherical vessel or hemisph. head, of inside major dia for an elliptical head, or 2 * Crown radius for the ASME torisph. head.

Value of constant, K is given by:

$$K = \frac{1}{6} \cdot \left[ 2 + \left( \frac{D}{D_1} \right)^2 \right]$$

where: $D_1$ = minor dia of elliptical head, mm

For ASME torisph. head, K = 0.885

**The EES Function:**

---

FUNCTION t_h(p, D, K, S_a, e_w)

"EES Function for min. thickness for spherical shells, hemisph. heads, Elliptical heads, or ASME torispherical heads:

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Inputs: p = design internal pressure, kPa; D = ID of sph.shell,or, hemisph. head, OR: inside major dia for an elliptical head,

OR: 2 * crown radius for an ASME torispherical head, mm;

S_a = allowable pressure, kPa; e_w = weld efficiency

Output: thickness of shell, mm, "

t_h = (p * D * K) / (2 * S_a * e_w - 0.2 * p)

END

"Example:"

p = 800 "kPa"

D = 3050 "mm"

S_a = 129200 "kPa"

e_w = 1; K = 0.5

"Then, we get:"

t_h = t_h(p, D, K, S_a, e_w)

"========================================================"

**Results:**

**Unit Settings: SI K kPa kJ mass deg**

D = 3050 [mm] $e_w$ = 1 K = 0.5 p = 800 [kPa] $S_a$ = 129200 [kPa]

$t_h$ = 4.724 [mm]

**Thus: t_h = 4.724 mm …Ans.**

"========================================================"

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## PROB.V-B.4

### WRITE AN EES FUNCTION FOR THICKNESS OF OUTER CYLINDRICAL SHELL OF A CRYOGENIC TANK:

**First, determine if it is a 'long cylinder' or 'short cylinder':**

**Test for a 'long' cylinder:**

$$L/D_o > 1.140\,(1 - \upsilon^2)^{1/4}\,(D_o/t)^{1/2}$$

**EES Procedure to determine if it is a long or short cylinder:**

---

PROCEDURE Test_for_long_cylinder(L, D_o, t, nu : LbyD_o, RHS, RESULT$)

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"To determine if it is a 'long cylinder' or 'short cylinder':

Test for a 'long' cylinder:

L/Do > 1.140 * (1 - nu^2)^(1/4) * (Do/t)^(1/2)

Inputs:L =length of cyl, m; D_o = OD of cyl, m; t = thickness, m; nu = Poisson's ratio"

"Outputs: LbyDo, RHS, RESULT "

```
LbyD_o = L / D_o

RHS = 1.14 * (1 - nu^2)^(1/4) * (D_o / t)^(1/2)

IF (LbyD_o) >= RHS THEN

    RESULT$ = ' It is along cylinder !'

ELSE

    RESULT$ = 'It is a short cylinder !'

ENDIF

END
```

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"Example:"

L = 2.25 "m"

D_o = 3.66 "m"

t = 0.012 "m"

nu = 0.27

"Then, we get:"

CALL Test_for_long_cylinder(L, D_o, t, nu : LbyD_o, RHS, RESULT$)

"========================================================"

**Results:**

**Unit Settings: SI K kPa kJ mass deg**

| | |
|---|---|
| $D_o$ = 3.66 [m] | L = 2.25 [m] |
| $LbyD_o$ = 0.6148 | $\nu$ = 0.27 |
| RESULT$ = 'It is a short cylinder !' | RHS = 19.54 |
| t = 0.012 [K] | |

**Thus: It is a short cylinder.**

"========================================================"

**For Long cylinder, thickness of outer shell is given by:**

**Failure by Elastic instability**:

$p_c$ = collapsing pressure = 4 * $p_a$, $p_a$ = atm. pressure, 4 is the factor of safety

$$t\_outershell\_longcyl = \left[\frac{p_c \cdot \left(1 - \nu^2\right)}{2 \cdot E}\right]^{\frac{1}{3}} \cdot D_0$$ ...for long cylinder

**For short cylinder, thickness of outer shell is calculated from:**

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$$p_c = \frac{2.42 \cdot E \cdot \left(\frac{t}{D_0}\right)^{\frac{5}{2}}}{\left(1 - \nu^2\right)^{\frac{3}{4}} \cdot \left[\left(\frac{L}{D_0}\right) - 0.45 \cdot \left(\frac{t}{D_0}\right)^{\frac{1}{2}}\right]}$$

**EES Function for thickness of outer shell of *long cylinder*:**

FUNCTION t_outer_long_cyl(p_c, nu, E, D_o)

"EES Function for thicknessouter cylinder of dewar vessel, LONG cyl, :

Inputs: p_c = critical pressure = 4 * p_a, kPa; D_o = OD of shell

E = Young's modulus, nu = Poisson's ratio

Output: thickness of shell, "

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t_outer_long_cyl = (p_c * (1 - nu^2) / (2 * E) * D_o^3)^(1/3)

END

```
"Example:"
D_o =168.3 "mm"
p_c = 4*101.3  "kPa"
nu = 0.28 "..Poisson's ratio"
E = 207*10^6  "kPa .... Young's Modulus"
"Then, we get:"
t_outer = t_outer_long_cyl(p_c, nu, E, D_o)
"========================================================"
```

---

```
"Example:"
D_o =168.3 "mm"
p_c = 4*101.3  "kPa"
nu = 0.28 "..Poisson's ratio"
E = 207*10^6  "kPa .... Young's Modulus"
"Then, we get:"
t_outer = t_outer_long_cyl(p_c, nu, E, D_o)
"========================================================"
```

**Results:**

**Unit Settings: SI K kPa kJ mass deg**

$D_o$ = 168.3 [mm] E = 2.070E+08 [kPa] $\nu$ = 0.28 $p_c$ = 405.2 [kPa]

$t_{outer}$ = 1.626 [mm]

```
"========================================================"
```

**EES Function for thickness of outer shell of short *cylinder*:**

For a short cylinder, we write an EES function for critical pressure, and that itself will calculate the thickness easily from the implicit equation, viz.

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$$p_c = \frac{2.42 \cdot E \cdot \left(\frac{t}{D_0}\right)^{\frac{5}{2}}}{\left(1 - \nu^2\right)^{\frac{3}{4}} \cdot \left[\left(\frac{L}{D_0}\right) - 0.45 \cdot \left(\frac{t}{D_0}\right)^{\frac{1}{2}}\right]}$$

**See the Function and example below:**

---

FUNCTION p_c(t_outershortcyl, Do, L, E, nu)

{Determines the thickness of outer cyl when it is a 'short cyl', of a dewar vessel ( mm) when collapsing pressure (p_c, kPa),

Outer Diameter (Do, mm), Youngs Mod.,( E, kPa) and Poissons ratio (nu) are given.

Note: p_ = 4 * p_a, where 4 is factor of safety, p_a = atm. pr. }

p_c := (2.42 * E * (t_outershortcyl / Do)^(5/2)) /( ((1 - nu^2)^(3/4)) * ((L / Do) - 0.45 * (t_outershortcyl / Do)^(1/2)))

END

"Example: see Barron, pp.369"

p_c = 4*101.3 "kPa"

nu = 0.27

L = 2.25 "m"

Do = 3.66 "m"

E = 200*10^6 "kPa"

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p_c = p_c(t_outershortcyl, Do, L, E, nu)

**Note:** This Function is for $p_c$. Since its value is given, but on the RHS, value of thickness is not known, EES calculates the same very easily.

**Results:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| Do = 3.66 [m] | E = 2.000E+08 [kPa] | L = 2.25 [m] |
| $\nu$ = 0.27 | $p_c$ = 405.2 [kPa] | $t_{outershortcyl}$ = 0.01074 [m] |

**i.e. thickness = 10.74 mm ….Ans.**

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## PROB.V-B.5

### WRITE AN EES FUNCTION FOR THICKNESS OF OUTER HEADS OF A CRYOGENIC TANK:

**Required head thickness for outer cylinder:**

For hemispherical, elliptical or torisph. head, (or for a spherical vessel), thickness is given by:

$$t\_head\_outer\_vessel = \left[ \frac{p_c \cdot \left[ 3 \cdot \left( 1 - v^2 \right) \right]^{\frac{1}{2}}}{0.5 \cdot E} \cdot R_0^{\,2} \right]^{\frac{1}{2}}$$

where:

$R_0$ = outside rad. of spherical head or spherical vessel, equivalent radius of elliptical head, or crown rad. of torisph. head.

---

**Equiv. radius (K1) for Elliptical heads:**

**D = Major dia, D1 = Minor dia,**

**Equiv. rad. = K1. D;**

**factor K1 is given in Table below:**

**Table 6.6** Equivalent radius for elliptical heads under external pressure. $R_0 = K_1 D$ and $D$ = major diameter of the ellipse, $D_1$ = minor diameter of the ellipse.

| $D/D_1$ | $K_1$ | $D/D_1$ | $K_1$ |
|---|---|---|---|
| 3.0 | 1.36 | 1.8 | 0.81 |
| 2.8 | 1.27 | 1.6 | 0.73 |
| 2.6 | 1.18 | 1.4 | 0.65 |
| 2.4 | 1.08 | 1.2 | 0.57 |
| 2.2 | 0.99 | 1.0 | 0.50 |
| 2.0 | 0.90 | | |

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**Example for head thickness calculation:**

**First, write the EES Function for critical pressure of outer vessel head:**

---

FUNCTION p_c_outer_head(t_outerhead, R_o, E, nu)

" Here, R_o = outside radius of spherical head or spherical vessel, equivalent radius of elliptical head,

OR: crown radius of torispherical head.

Equiv. radius for elliptical head is given by R_o = K1. D where D is the major dia and K1 is the factor given in Table 6.6.

The cpllapsing pressure p_c is given by: p_c = 4. p_a where 4 is the factor of safety, and p_a is allowable external pressure

(i.e. atmospheric pressure for the outer shell or head of a dewar vessel)."

p_c_outer_head =( 0.5 * E *( t_outerhead / R_o)^2) / ( 3 * (1 - nu^2))^0.5

END

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```
"Example: a hemispherical head, D_o = 3.66 m"

p_c = 4*101.3  "kPa ... critical pressure for outer head."

R_o = 3.66/2 "m"

nu = 0.27 "Poisson's ratio"

E = 200*10^6 "kPa"

"To find thickness of head:"

p_c = p_c_outer_head(t_outerhead, R_o, E, nu) "...calculates t_outerhead"
```

**Results:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $E = 2.000E+08$ [kPa] | $\nu = 0.27$ | $p_c = 405.2$ [kPa] |
| $R_o = 1.83$ [m] | $t_{outerhead} = 0.004757$ [m] | |

**Thus: thickness of outer head = 0.004757 m = 4.76 mm … Ans.**

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```
"======================================================"
```

## PROB.V-B.6

**DETERMINE THE INNER VESSEL AND OUTER VESSEL MINIMUM THICKNESSES FOR A SPHERICAL LH2 VESSEL HAVING A NOMINAL CAPACITY OF 2000 M^3 WITH A 10% ULLAGE VOLUME. THE OUTER SHELL O.D. IS 1.22 M LARGER THAN THE INNER SHELL O.D. THE INNER SHELL IS CONSTRUCTED OF 304 SS WITH SPOT EXAMINED BUTT JOINTS WITH COMPLETE PENETRATION WELDS. THE OUTER SHELL IS CONSTRUCTED OF CARBON STEEL - SA 285, GRADE C. THE DESIGN PRESSURE IS 700 KPA ABSOLUTE. [1]**

**Solution:**

---

V_inner = 2000 + 0.1 * 2000 "m^3"

V_inner = (4 / 3) * pi * R_o^3 "....determines outer rad. R_o, m"

D_inner = 2 * R_o "m.... outer dia"

"Therefore:"

D_outer = D_inner + 1.22 "m ... outer shell dia "

"For SS 304:"

s_a = 129.2 * 10^3 "kPa .... allowable stress for SS 304"

p = 700 "kPa..desin pressure, .by data"

e_w = 0.85 "..weld effcy."

K = 0.5 "...for sph. shell"

"Then, thickness of spherical shell, t_h:"

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D = D_inner

t_h_innershell = t_innersph(p, D, K, s_a, e_w)

"We get:"

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $D = 16.14$ [mm] | $D_{inner} = 16.14$ [m] | $D_{outer} = 17.36$ [m] |
| $e_w = 0.85$ | $K = 0.5$ | $p = 700$ [kPa] |
| $R_o = 8.068$ [m] | $s_a = 129200$ [kPa] | $t_{h,innershell} = 0.02573$ [m] |
| $V_{inner} = 2200$ [$m^3$] | | |

"i.e. we get, t_h_inner shell = 0.0257 m = 26 mm.

Now, tolerance for metric plates is 0.3 mm under the standard thickness.

So, the nominal thickness would be (26 mm + 0.3 mm) = 26.3 mm.

**Therefore, select 28 mm plate for inner shell; see Table 6.4"**

"Therefore, OD of inner shell:"

OD_inner = D_inner + 2 * 0.028

OD_outershell = OD_inner + 1.22

**"Now, thickness of outer sph. shell:"**

p_c = 4 * 101.3 "kPa... crit. pressure"

E = 200 * 10^6 "kPa"

nu = 0.27

R_outer = OD_outershell / 2

"Then:"

p_c = p_c_outer_head(t_outerhead, R_outer, E, nu)

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**We get:**

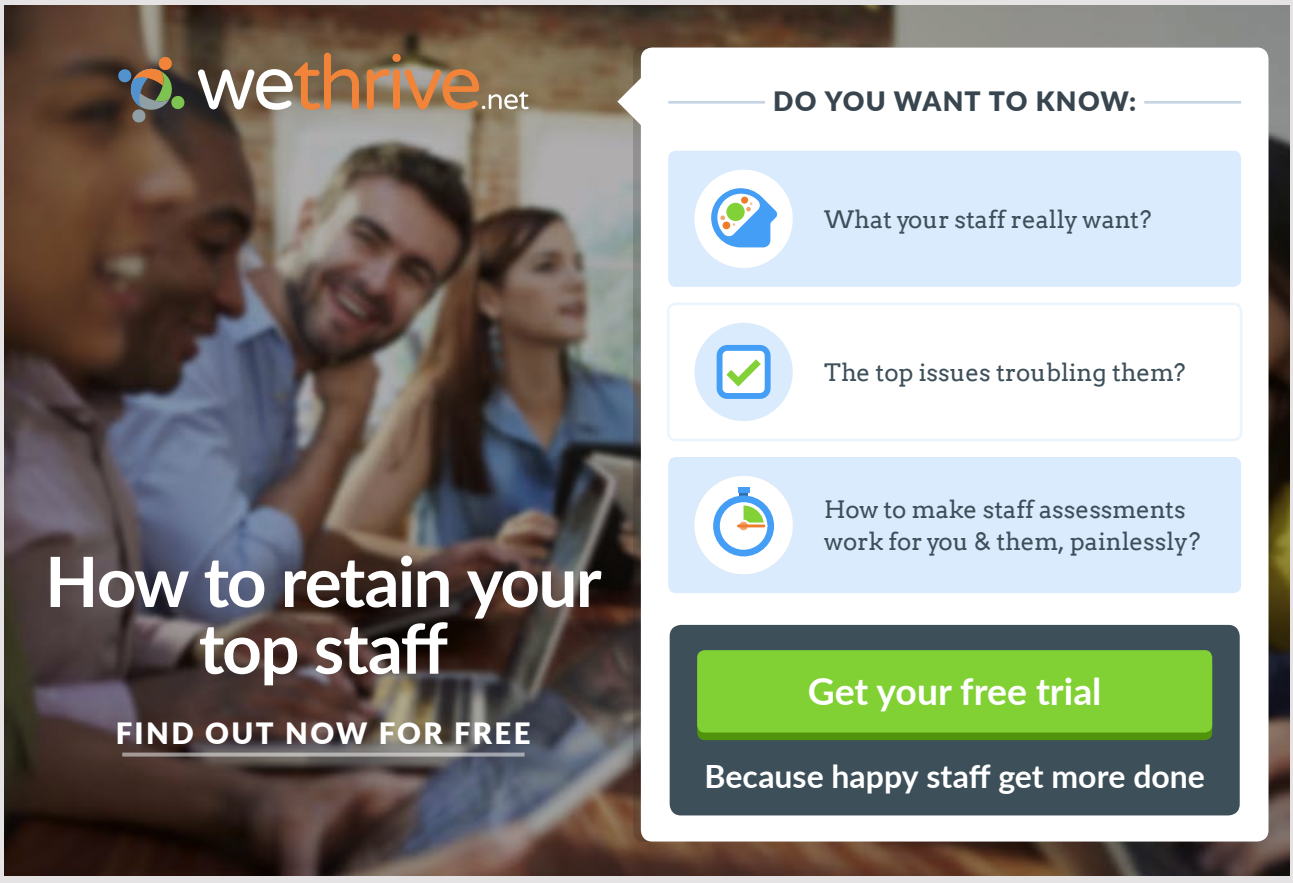
**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| D = 16.14 [mm] | $D_{inner}$ = 16.14 [m] | $D_{outer}$ = 17.36 [m] |
| E = 2.000E+08 [kPa] | $e_w$ = 0.85 | K = 0.5 |
| v = 0.27 | $OD_{inner}$ = 16.19 | $OD_{outershell}$ = 17.41 |
| p = 700 [kPa] | $p_c$ = 405.2 [kPa] | $R_o$ = 8.068 [m] |
| $R_{outer}$ = 8.706 | $s_a$ = 129200 [kPa] | $t_{h,innershell}$ = 0.02573 [m] |
| $t_{outerhead}$ = 0.02263 [m] | $V_{inner}$ = 2200 [$m^3$] | |

"Then: t_outerhead = 0.02263 m = 23 mm

**Therefore, choose 25 mm plate for outer shell.... Ans. "**

"=========="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## PROB.V-B.7

**THE INNER SHELL OF A HORIZONTAL CYLINDRICAL LIQUID-NITROGEN DEWAR HAS A CYLINDRICAL LENGTH OF 24 M (78.74 FT) AND AN INSIDE DIAMETER OF 1.829 M (72 IN.). THE INNER VESSEL IS CONSTRUCTED OF 304 STAINLESS STEEL WITH 100 PERCENT RADIO-GRAPHED WELDS. THE WORKING PRESSURE FOR THE INNER VESSEL IS 620 KPA (ABSOLUTE) OR 89.9 PSIA. ELLIPTICAL HEADS WITH D/D1 = 2 ARE USED AS THE END CLOSURES FOR THE VESSEL. DETERMINE: THE MINIMUM THICKNESS OF THE INNER SHELL AND HEADS. THE ULLAGE VOLUME IS 10 PERCENT. [1]**

**Solution:**"Inner vessel design:"

"Material: SS 304, 100% radiographed welds."

L = 24 "m ... length of cyl"

D_inner = 1.829 "m.... inside dia of cyl. shell"

p = 620 "kPa ... inside pressure"

"Two elliptical heads, with D / D1 = 2"

"Therefore, vol. of cyl. section:"

V_cyl = (pi * D_inner^2) / 4 * L "m^3"

"Vol. of two elliptical heads:"

V_heads = 2 * (pi * D_inner^3)/24 "m^3"

"Therefore, total inner cyl. volume:"

V_inner = V_cyl + V_heads "m^3"

"Including 10% ullage volume, we get:"

V_innertotal = V_inner + 0.1 * V_inner "m^3"

"Thickness of inner cyl. shell:"

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"Allowable stress for SS 304:"

S_a = 129.2 * 10^3 "kPa"

e_w = 1 "...weld effcy."

t_inner_shell = t_innercyl(p, D_inner, S_a, e_w) "m .... thickness of inner shell"

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $D_{inner}$ = 1.829 [m] | $e_w$ = 1 | L = 24 [m] |
| p = 620 [kPa] | $S_a$ = 129200 [kPa] | $t_{inner,shell}$ = 0.004401 [m] |
| $V_{cyl}$ = 63.06 [$m^3$] | $V_{heads}$ = 1.602 [$m^3$] | $V_{inner}$ = 64.66 [$m^3$] |
| $V_{innertotal}$ = 71.12 [$m^3$] | | |

**We get: t_inner_shell = 0.004401 m = 4.401 mm**

**i.e. we choose 5 mm thick plate for inner cylindrical shell … Ans.**

**Thickness of elliptical heads of inner vessel:**

Min. thickness for spherical shells, hemisph. heads, Elliptical heads, or ASME torispherical heads is given by:

$$t_h = \frac{p \cdot D \cdot K}{2 \cdot S_a \cdot e_w - 0.2 \cdot p} = \frac{p \cdot D_0 \cdot K}{2 \cdot S_a \cdot e_w + 2 \cdot p \cdot (K - 0.1)}$$

where:

D = inside dia of spherical vessel or hemisph. head, of inside **major dia** for an elliptical head, or 2 * Crown radius for the ASME torisph. head.

Value of constant, K is given by:

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$$K=\frac{1}{6}\cdot\left[2+\left(\frac{D}{D_1}\right)^2\right]$$

where: D1 = **minor dia** of elliptical head

For ASME torisph. head, K = 0.885

For D/D1 = 2, we get: K = 1

Therefore, we get:

$$t_h := \frac{p \cdot D \cdot K}{2 \cdot S_a \cdot e_w - 0.2 \cdot p}$$

K = 1 "...for D/D1 = 2 for elliptical heads"

t_h = ( p * D_inner * K ) / (2 * S_a * e_w - 0.2 * P) "m... thickness of elliptical head"

We get:

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $D_{inner}$ = 1.829 [m] | $e_w$ = 1 | K = 1 |
| L = 24 [m] | p = 620 [kPa] | $S_a$ = 129200 [kPa] |
| $t_h$ = 0.004391 [mm] | $t_{inner,shell}$ = 0.004401 [m] | $V_{cyl}$ = 63.06 [$m^3$] |
| $V_{heads}$ = 1.602 [$m^3$] | $V_{inner}$ = 64.66 [$m^3$] | $V_{innertotal}$ = 71.12 [$m^3$] |

**We see that thickness of elliptical heads is: t_h = 0.004391 m = 4.39 mm**

**So, we choose 5 mm plate for inner shell elliptical heads….. Ans.**

==========

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## PROB.V-B.8

**THE OUTER SHELL OF A LIQUID-NITROGEN STORAGE VESSEL HAS A CYLINDRICAL LENGTH OF 24.8 M (81.36 FT) AND AN OUTSIDE DIAMETER OF 2.438 M (96 IN.). THE OUTER VESSEL IS CONSTRUCTED OF CARBON STEEL, SA-285, GRADE C. ELLIPTICAL HEADS WITH D/ D1 = 2 ARE USED AS THE END CLOSURES FOR THE VESSEL. EIGHT STIFFENING RINGS (TWO MAIN SUPPORT RINGS AND SIX INTERMEDIATE RINGS) SPACED 2.75 M (108.3 IN.) APART ARE USED ON THE OUTER SHELL. DETERMINE: THE MINIMUM THICKNESS OF THE OUTER SHELL AND HEADS. [1]**

**Solution:**

**This is part of a problem from Ref. [1].**

"For Carbon steel, from Table 6.5, we have:"

E = 200 * 10^6 "kPa....Young's modulus"

nu = 0.27 "...Poisson's ratio"

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L = 2.75 "m...distance between stiffening rings"

D_o = 2.438 "m"

p_c = 4 * 101.3 "kPa.... critical pressure"

"Thickness of outer cylindrical shell:"

"First, assume that it is a short cylinder and find out the shell thickness. Then, verify, applying the test for a long cylinder, that it is really a short cylinder:"

---

"Using the EES Function already written, for a short cylinder:"

p_c = p_c(t_outershortcyl, D_o, L, E, nu) "..EES Function for p_c; But, p_c is alreagy known, so EES will calculate the unknown, viz. t_outershortcyl"

We get:

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $D_o$ = 2.438 [mm] | E = 2.000E+08 [kPa] | L = 2.75 [m] |
| $\nu$ = 0.27 | $p_c$ = 405.2 [kPa] | $t_{outershortcyl}$ = 0.009182 [m] |

"Thus: we get: t_outershortcyl = 0.009182 m = 9.182 mm "

**"Therefore, choose 10 mm nominal plate from Table 6.4"**

**"Now, apply the test to see if it is really a short cylinder or not:"**

CALL Test_for_long_cylinder(L, D_o, t_outershortcyl, nu : LbyD_o, RHS, RESULT$)

We get:

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**Unit Settings: SI K kPa kJ mass deg**

$D_o$ = 2.438 [m]

L = 2.75 [m]

ν = 0.27

RESULT$ = 'It is a short cylinder !'

$t_{outershortcyl}$ = 0.009182 [m]

E = 2.000E+08 [kPa]

$LbyD_o$ = 1.128

$p_c$ = 405.2 [kPa]

RHS = 18.23

**"Therefore, confirmed that it is a *short cylinder.*"**

**Thickness of elliptical heads:**

**We have for elliptical head thickness:**

---

"For elliptical heads, with D / D1 = 2, we have, from Table 6.6:"

K1 = 0.9

R_o = K1 * D_o "..where R_o = equiv radius of elliptical heads under external pressure, D1 = minor dia, D_o = major dia of elliptical heads."

p_c = p_c_outer_head(t_outerhead, R_o, E, nu)

" Above EES Function is for p_c when cylinder head is subjected to external pressure; but, here p_c is known.

So, EES will calculate the unknown, viz. t_outerhead."

**And, we get:**

**Unit Settings: SI K kPa kJ mass deg**

$D_o$ = 2.438 [m]

K1 = 0.9

$LbyD_o$ = 1.128

$p_c$ = 405.2 [kPa]

RHS = 18.23

$t_{outerhead}$ = 0.005704 [m]

E = 2.000E+08 [kPa]

L = 2.75 [m]

ν = 0.27

RESULT$ = 'It is a short cylinder !'

$R_o$ = 2.194 [m]

$t_{outershortcyl}$ = 0.009182 [m]

**i.e. t_outerhead = 0.005704 m = 5.704 mm.**

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**So, use 6 mm thick head……Ans.**

==========

## PROB. V-B.9

### WRITE EES FUNCTIONS/ PROCEDURES FOR THERMAL CONDUCTIVITY, THERMAL CONDUCTIVITY INTEGRALS, AND THERMAL EXPANSION FOR A FEW MATERIALS USED IN CRYOGENICS.

**Solution:**

**Refer to Tables 6.7 A, B and C.**

Above Tables are from Ref. [1]. For all these data, we can, of course, refer to NIST website.

However, in the present case, we will copy these Tables as Lookup Tables in EES and determine the property required at any temp by linear interpolation. The method is explained below:

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**EES Functions for Thermal conductivities of some materials:**

Copy the Table 6.7 A as a Lookup Table, by name: 'Th_cond values' in EES:

Lookup Table

Temp vs Th cond of SS 304 | **Th_cond_values** | Th-cond-Integrals | DELTALbyLE05

| Paste Special | 1 Temp [K] | 2 BeCu-$k_t$ [W/m.K] | 3 AL6063T5-$k_t$ [W/m.K] | 4 Steel1020-$k_t$ [W/m.K] | 5 SS304-$k_t$ [W/m.K] | 6 Monel-$k_t$ [W/m.K] | 7 Teflon-$k_t$ [W/m.K] |
|---|---|---|---|---|---|---|---|
| **Row 1** | 4 | 1.9 | 34 | 3 | 0.24 | 0.43 | 0.046 |
| Row 2 | 10 | 4.8 | 86 | 11.5 | 0.77 | 1.74 | 0.096 |
| Row 3 | 20 | 10.6 | 170 | 24 | 1.95 | 4.3 | 0.141 |
| Row 4 | 30 | 16.2 | 230 | 32 | 3.3 | 6.9 | 0.174 |
| Row 5 | 40 | 21 | 270 | 38.6 | 4.7 | 9 | 0.193 |
| Row 6 | 50 | 26.1 | 280 | 47.6 | 5.8 | 10.95 | 0.208 |
| Row 7 | 60 | 30 | 270 | 53.6 | 6.8 | 12.09 | 0.219 |
| Row 8 | 70 | 33.7 | 248 | 57.5 | 7.6 | 13.06 | 0.228 |
| Row 9 | 80 | 37 | 230 | 60 | 8.26 | 13.9 | 0.235 |
| Row 10 | 90 | 40.1 | 222 | 61.8 | 8.86 | 14.63 | 0.241 |
| Row 11 | 100 | 43 | 216 | 62.9 | 9.4 | 15.27 | 0.245 |
| Row 12 | 120 | 48.4 | 207 | 64.1 | 10.36 | 16.26 | 0.251 |
| Row 13 | 140 | 53.3 | 201 | 64.6 | 11.17 | 17.34 | 0.255 |
| Row 14 | 160 | 57.6 | 200 | 64.8 | 11.86 | 18.25 | 0.257 |
| Row 15 | 180 | 61.5 | 200 | 64.9 | 12.47 | 19.02 | 0.258 |
| Row 16 | 200 | 65 | 200 | 65 | 13 | 19.69 | 0.259 |
| Row 17 | 250 | 72.4 | 200 | 65 | 14.07 | 21.02 | 0.26 |
| Row 18 | 300 | 78.5 | 200 | 65 | 14.9 | 22 | 0.26 |

Now, use the built-in Interpolate1 function in EES to interpolate the Th. cond values for a given material against temp.

See the examples below:

---

FUNCTION Th_cond_BeCu(T)

"Th. cond. of BeCu from Table in Barron... Lookup Table in EES-linear interpolation.

k_t in W/m.K, T in K"

{ Finds Th. cond. in the range: T =4 - 300 K:}

IF (T <4) or (T > 300) THEN

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```
    CALL ERROR('Temp. must be between 4 and 300 K !')
ENDIF
Th_cond_BeCu= interpolate1('Th_cond_values', 'Temp', 'BeCu-k_t', Temp = T)
END
"============================================================="
"Example:"
T = 85 "K"
k_t = Th_cond_BeCu(T) "W/m.K"
```

**Unit Settings: SI K kPa kJ mass deg**

$k_t$ = 38.5500 [W/m.K]  T = 85 [K]

```
"============================================================="
FUNCTION Th_cond_AL6063T5(T)
"Th. cond. of AL-6063-T5 from Table in Barron... Lookup Table in EES-linear interpolation.
k_t in W/m.K, T in K"
{ FindsTh. cond. in the range: T = 4 - 300 K:}
IF (T <4) or (T > 300) THEN
    CALL ERROR('Temp. must be between 4 and 300 K !')
ENDIF
Th_cond_AL6063T5= interpolate1('Th_cond_values', 'Temp', 'AL6063T5-k_t', Temp = T)
END
"Example:"
```

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T = 85 "K"

k_t = Th_cond_AL6063T5(T)"W/m.K"

**Unit Settings: SI K kPa kJ mass deg**

$k_t$ = 226.0000 [W/m.K]  T = 85 [K]

"============================================================="

FUNCTION Th_cond_Steel1020(T)

"Th. cond. of Steel 1020 from Table in Barron... Lookup Table in EES-linear interpolation.

k_t in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (T <4) or (T > 300) THEN

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CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF

Th_cond_Steel1020= interpolate1('Th_cond_values', 'Temp', 'Steel1020-k_t', Temp = T)

END

"Example:"

T = 85 "K"

k_t = Th_cond_Steel1020(T) "W/m.K"

**Unit Settings: SI K kPa kJ mass deg**

$k_t$ = 60.9000 [W/m.K]  T = 85 [K]

"============================================================"

FUNCTION Th_cond_SS304(T)

"Th. cond. of SS 304 from Table in Barron... Lookup Table in EES-linear interpolation.

k_t in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (T <4) or (T > 300) THEN

CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF

Th_cond_SS304= interpolate1('Th_cond_values', 'Temp', 'SS304-k_t', Temp = T)

END

"Example:"

T = 85 "K"

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k_t = Th_cond_SS304(T) "W/m.K"

**Unit Settings: SI K kPa kJ mass deg**

$k_t$ = 8.5600 [W/m.K]  T = 85 [K]

"============================================================"

FUNCTION Th_cond_Monel(T)

"Th. cond. of Monel from Table in Barron... Lookup Table in EES-linear interpolation.

k_t in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (T <4) or (T > 300) THEN

    CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF

Th_cond_Monel= interpolate1('Th_cond_values', 'Temp', 'Monel-k_t', Temp = T)

END

"Example:"

T = 85 "K"

k_t = Th_cond_Monel(T) "W/m.K"

**Unit Settings: SI K kPa kJ mass deg**

$k_t$ = 14.2650 [W/m.K]  T = 85 [K]

"============================================================"

FUNCTION Th_cond_Teflon(T)

"Th. cond. of Teflon from Table in Barron... Lookup Table in EES-linear interpolation.

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```
k_t in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (T <4) or (T > 300) THEN

    CALL ERROR('Temp. must be between 4 and 300 K !')

ENDIF

Th_cond_Teflon= interpolate1('Th_cond_values', 'Temp', 'Teflon-k_t', Temp = T)

END

"Example:"

T = 85 "K"

k_t = Th_cond_Teflon(T) "W/m.K"
```

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**Unit Settings: SI K kPa kJ mass deg**

$k_t$ = 0.2380 [W/m.K]  T = 85 [K]

"============================================================="

**EES Functions for Thermal conductivity integrals of some materials:**

Copy the Table 6.7 B as a Lookup Table, by name: 'Th-cond-Integrals' in EES:

Lookup Table

Temp vs Th cond of SS 304 | Th_cond_values | **Th-cond-Integrals** | DELTALbyLE05

| Paste Special | 1 Temp [K] | 2 BeCu [W/m] | 3 AL6063T5 [W/m] | 4 Steel1020 [W/m] | 5 SS304 [W/m] | 6 Monel [W/m] | 7 Teflon [W/m] |
|---|---|---|---|---|---|---|---|
| **Row 1** | 4 | 0 | 0 | 0 | 0 | 0 | 0 |
| Row 2 | 10 | 19 | 360 | 43 | 2.9 | 6.3 | 0.44 |
| Row 3 | 20 | 95 | 1650 | 222 | 16.3 | 36.4 | 1.64 |
| Row 4 | 30 | 229 | 3650 | 502 | 42.4 | 92.9 | 3.23 |
| Row 5 | 40 | 415 | 6200 | 867 | 82.4 | 173 | 5.08 |
| Row 6 | 50 | 650 | 8950 | 1310 | 135 | 273 | 7.16 |
| Row 7 | 60 | 930 | 11700 | 1810 | 198 | 368 | 9.36 |
| Row 8 | 70 | 1250 | 14300 | 2360 | 270 | 513 | 11.6 |
| Row 9 | 80 | 1600 | 16700 | 2950 | 349 | 647 | 13.9 |
| Row 10 | 90 | 1990 | 19000 | 3550 | 436 | 791 | 16.3 |
| Row 11 | 100 | 2400 | 21100 | 4170 | 528 | 940 | 18.7 |
| Row 12 | 120 | 3300 | 25300 | 5450 | 726 | 1260 | 23.7 |
| Row 13 | 140 | 4320 | 29300 | 6750 | 939 | 1590 | 28.7 |
| Row 14 | 160 | 5440 | 33300 | 8050 | 1170 | 1950 | 33.8 |
| Row 15 | 180 | 6640 | 37300 | 9350 | 1410 | 2320 | 39 |
| Row 16 | 200 | 7910 | 41300 | 10700 | 1660 | 2710 | 44.2 |
| Row 17 | 250 | 11300 | 51300 | 13900 | 2340 | 3730 | 57.2 |
| Row 18 | 300 | 15000 | 61300 | 17200 | 3060 | 4800 | 70.2 |

Now, use the built-in Interpolate1 function in EES to interpolate the Th. cond integral values for a given material against temp.

Note that in the EES Procedures below, we have written Th. cond integrals between any two given temps TL and TH, since it is more useful to calculate the heat transfer between those two temps taking in to account the variation of thermal conductivity between those two temps.

See the examples below:

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```
PROCEDURE k_t_Integral_BeCu(TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

"Th. cond. integral for BeCu in temp range TL to TH ... from Table in Barron... Lookup
Table in EES-linear interpolation.

k_t-Integral in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (TH > 300) THEN

    CALL ERROR('TH must be 300 K or lower !')

ENDIF

IF (TL < 4) THEN

   TL = 4

ENDIF

Integral_at_TL:= interpolate1('Th-cond-Integrals', 'Temp', 'BeCu', Temp = TL)

Integral_at_TH:= interpolate1('Th-cond-Integrals', 'Temp', 'BeCu', Temp = TH)

Integral_TL_TH := Integral_at_TH - Integral_at_TL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL k_t_Integral_BeCu( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)
```

**Unit Settings: SI K kPa kJ mass deg**

$Integral_{at,TH} = 15000$ $Integral_{at,TL} = 1495$ $Integral_{TL,TH} = 13505$ [W/m]

TH = 300 [K] TL = 77 [K]

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"============================================================"

PROCEDURE k_t_Integral_AL6063T5( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

"Th. cond. integral for AL6063T5 in temp range TL to TH ... from Table in Barron... Lookup Table in EES-linear interpolation.

k_t-Integral in W/m.K, T in K"

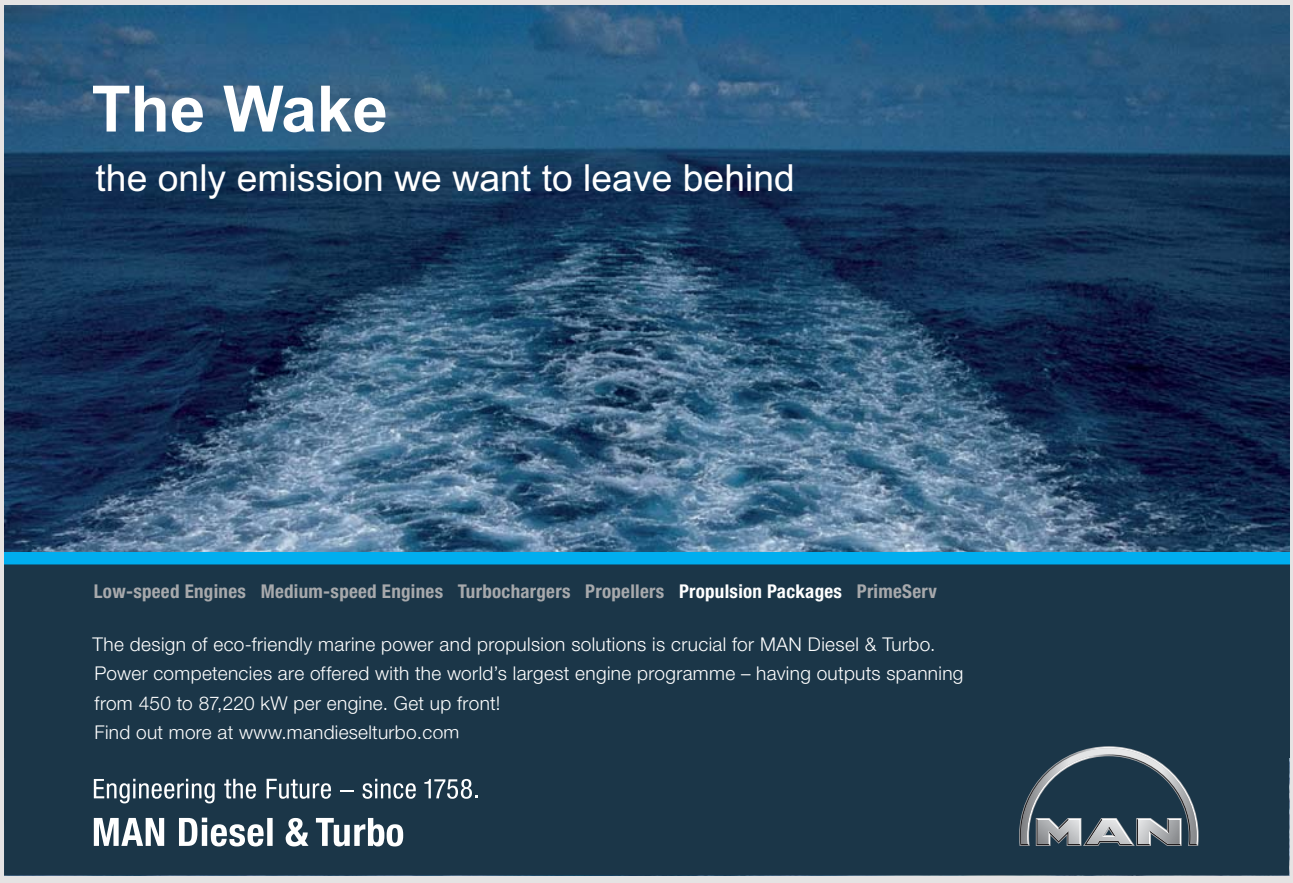
{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (TH > 300) THEN

CALL ERROR('TH must be 300 K or lower !')

ENDIF

IF (TL < 4) THEN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```
    TL = 4

ENDIF

Integral_at_TL:= interpolate1('Th-cond-Integrals', 'Temp', 'AL6063T5', Temp = TL)

Integral_at_TH:= interpolate1('Th-cond-Integrals', 'Temp', 'AL6063T5', Temp = TH)

Integral_TL_TH := Integral_at_TH - Integral_at_TL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL k_t_Integral_AL6063T5( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)
```

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $Integral_{at,TH}$ = 61300 [W/m] | $Integral_{at,TL}$ = 15980 [W/m] | $Integral_{TL,TH}$ = 45320 [W/m] |
| TH = 300 [K] | TL = 77 [K] | |

```
"============================================================="

PROCEDURE k_t_Integral_Steel1020( TL, TH:Integral_at_TL, Integral_at_TH, Integral_
TL_TH)

"Th. cond. integral for Steel1020 in temp range TL to TH ... from Table in Barron...
Lookup Table in EES-linear interpolation.

k_t-Integral in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (TH > 300) THEN

    CALL ERROR('TH must be 300 K or lower !')
```

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ENDIF

IF (TL < 4) THEN

TL = 4

ENDIF

Integral_at_TL:= interpolate1('Th-cond-Integrals', 'Temp', 'Steel1020', Temp = TL)

Integral_at_TH:= interpolate1('Th-cond-Integrals', 'Temp', 'Steel1020', Temp = TH)

Integral_TL_TH := Integral_at_TH - Integral_at_TL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL k_t_Integral_Steel1020( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

**Unit Settings: SI K kPa kJ mass deg**

$Integral_{at,TH}$ = 17200 [W/m] $Integral_{at,TL}$ = 2773 [W/m] $Integral_{TL,TH}$ = 14427 [W/m]

TH = 300 [K] TL = 77 [K]

"============================================================"

PROCEDURE k_t_Integral_SS304(TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

"Th. cond. integral for SS304 in temp range TL to TH ... from Table in Barron... Lookup Table in EES-linear interpolation.

k_t-Integral in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (TH > 300) THEN

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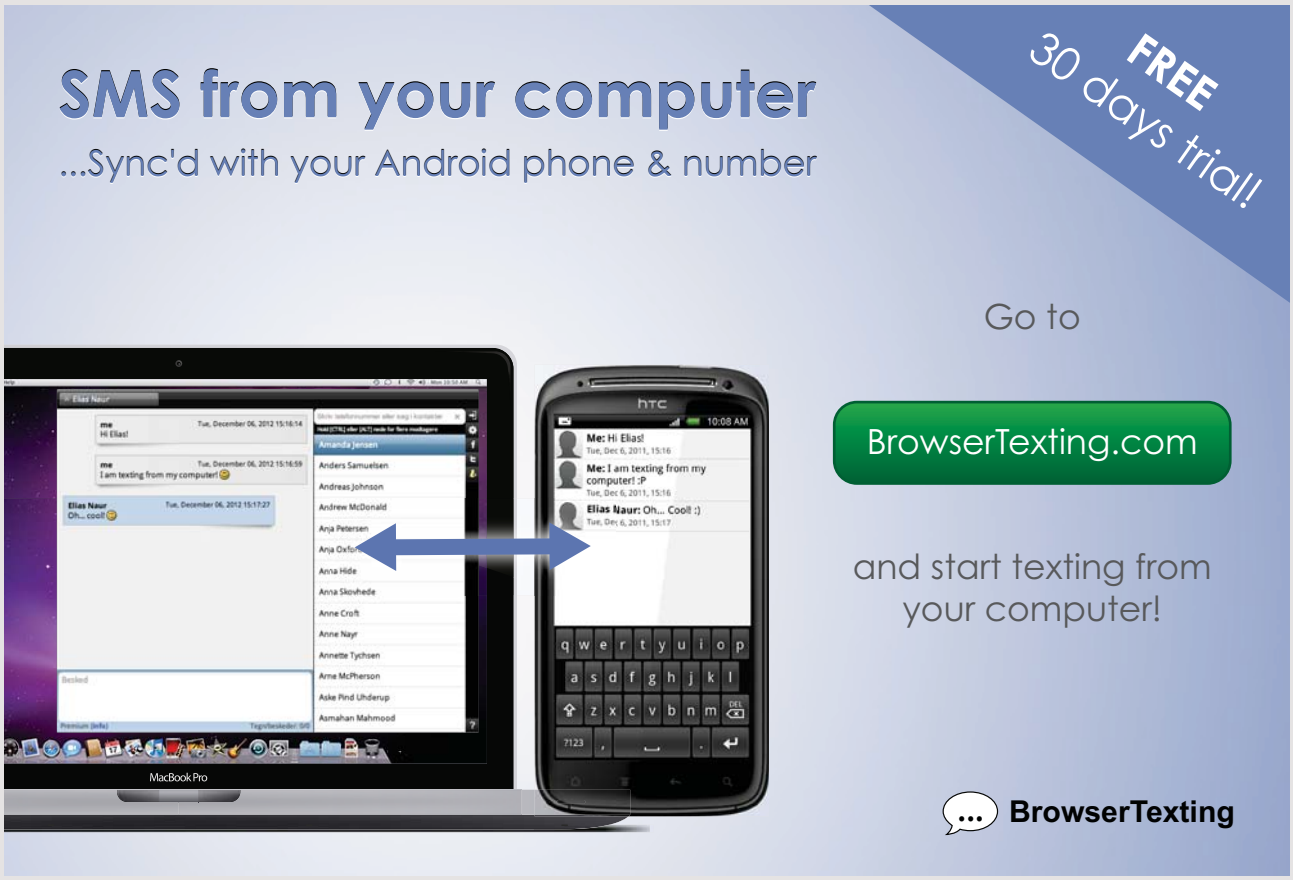
```
    CALL ERROR('TH must be 300 K or lower !')

ENDIF

IF (TL < 4) THEN

    TL = 4

ENDIF

Integral_at_TL:= interpolate1('Th-cond-Integrals', 'Temp', 'SS304', Temp = TL)

Integral_at_TH:= interpolate1('Th-cond-Integrals', 'Temp', 'SS304', Temp = TH)

Integral_TL_TH := Integral_at_TH - Integral_at_TL

END
```

"Example:"

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TL = 77 "K"

TH = 300 "K"

CALL k_t_Integral_SS304( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

$Integral_{at,TH}$ = 3060 [W/m] $Integral_{at,TL}$ = 325.3 [W/m] $Integral_{TL,TH}$ = 2735 [W/m]

TH = 300 [K] TL = 77 [K]

"============================================================="

PROCEDURE k_t_Integral_Monel( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

"Th. cond. integral for Monel in temp range TL to TH ... from Table in Barron... Lookup Table in EES-linear interpolation.

k_t-Integral in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (TH > 300) THEN

CALL ERROR('TH must be 300 K or lower !')

ENDIF

IF (TL < 4) THEN

TL = 4

ENDIF

Integral_at_TL:= interpolate1('Th-cond-Integrals', 'Temp', 'Monel', Temp = TL)

Integral_at_TH:= interpolate1('Th-cond-Integrals', 'Temp', 'Monel', Temp = TH)

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```
Integral_TL_TH := Integral_at_TH - Integral_at_TL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL k_t_Integral_Monel( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)
```

**Unit Settings: SI K kPa kJ mass deg**

$Integral_{at,TH}$ = 4800 [W/m] $Integral_{at,TL}$ = 606.8 [W/m] $Integral_{TL,TH}$ = 4193 [W/m]

TH = 300 [K] TL = 77 [K]

```
"============================================================="

PROCEDURE k_t_Integral_Teflon(TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

"Th. cond. integral for Teflon in temp range TL to TH ... from Table in Barron... Lookup
Table in EES-linear interpolation.

k_t-Integral in W/m.K, T in K"

{ FindsTh. cond. in the range: T = 4 - 300 K:}

IF (TH > 300) THEN

    CALL ERROR('TH must be 300 K or lower !')

ENDIF

IF (TL < 4) THEN

   TL = 4
```

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ENDIF

Integral_at_TL:= interpolate1('Th-cond-Integrals', 'Temp', 'Teflon', Temp = TL)

Integral_at_TH:= interpolate1('Th-cond-Integrals', 'Temp', 'Teflon', Temp = TH)

Integral_TL_TH := Integral_at_TH - Integral_at_TL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL k_t_Integral_Teflon( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

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$Integral_{at,TH}$ = 70.2 [W/m]  $Integral_{at,TL}$ = 13.21 [W/m]  $Integral_{TL,TH}$ = 56.99 [W/m]

TH = 300 [K]  TL = 77 [K]

"================================================================"

**EES Functions for Thermal expansion of some materials:**

Copy the Table 6.7 C as a Lookup Table, by name: 'DELTALbyLE05' in EES:

This Table is given in two-halves for clarity in reading:

Lookup Table

Temp vs Th cond of SS 304 | Th_cond_values | Th-cond-Integrals | **DELTALbyLE05**

| Paste Special | 1 Temp [K] | 2 BeCu [-] | 3 Aluminum [-] | 4 Steel1020 [-] | 5 SS304 [-] | 6 Monel [-] | 7 Invar [-] |
|---|---|---|---|---|---|---|---|
| **Row 1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Row 2 | 20 | 0 | 0 | 0 | 0 | 0 | 0 |
| Row 3 | 40 | 1 | 2 | 1 | 0 | 1 | 0 |
| Row 4 | 50 | 3 | 5 | 2 | 2 | 3 | 0 |
| Row 5 | 60 | 7 | 10 | 4 | 5 | 6 | 0 |
| Row 6 | 70 | 12 | 16 | 7 | 11 | 10 | 1 |
| Row 7 | 80 | 20 | 24 | 10 | 17 | 15 | 2 |
| Row 8 | 90 | 29 | 34 | 15 | 25 | 21 | 3 |
| Row 9 | 100 | 39 | 45 | 20 | 35 | 26 | 5 |
| Row 10 | 120 | 61 | 72 | 32 | 55 | 45 | 9 |
| Row 11 | 140 | 85 | 103 | 47 | 78 | 64 | 13 |
| Row 12 | 160 | 110 | 138 | 64 | 103 | 84 | 18 |
| Row 13 | 180 | 137 | 175 | 82 | 129 | 107 | 23 |
| Row 14 | 200 | 165 | 214 | 101 | 157 | 130 | 29 |
| Row 15 | 250 | 242 | 318 | 155 | 229 | 193 | 41 |
| Row 16 | 300 | 329 | 431 | 210 | 307 | 261 | 54 |

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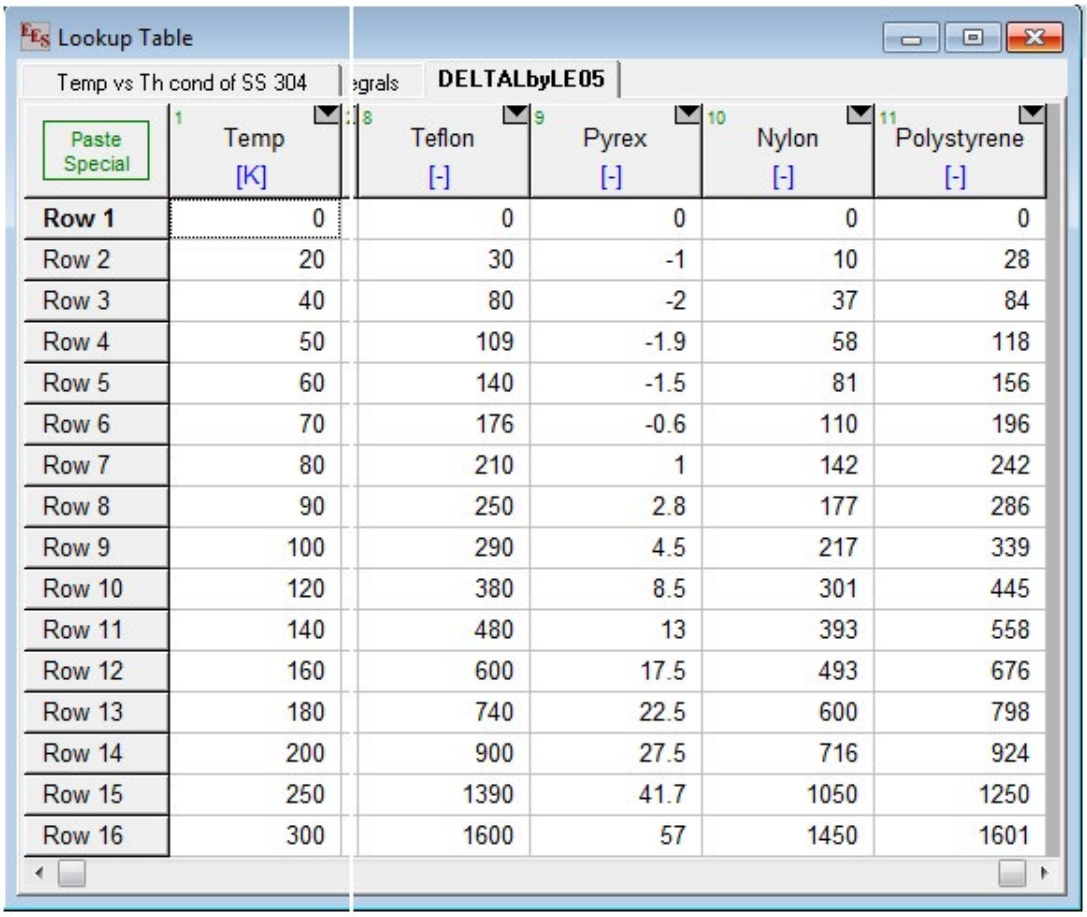

Lookup Table

Temp vs Th cond of SS 304 | grals | DELTALbyLE05

| Paste Special | 1 Temp [K] | 8 Teflon [-] | 9 Pyrex [-] | 10 Nylon [-] | 11 Polystyrene [-] |
|---|---|---|---|---|---|
| Row 1 | 0 | 0 | 0 | 0 | 0 |
| Row 2 | 20 | 30 | -1 | 10 | 28 |
| Row 3 | 40 | 80 | -2 | 37 | 84 |
| Row 4 | 50 | 109 | -1.9 | 58 | 118 |
| Row 5 | 60 | 140 | -1.5 | 81 | 156 |
| Row 6 | 70 | 176 | -0.6 | 110 | 196 |
| Row 7 | 80 | 210 | 1 | 142 | 242 |
| Row 8 | 90 | 250 | 2.8 | 177 | 286 |
| Row 9 | 100 | 290 | 4.5 | 217 | 339 |
| Row 10 | 120 | 380 | 8.5 | 301 | 445 |
| Row 11 | 140 | 480 | 13 | 393 | 558 |
| Row 12 | 160 | 600 | 17.5 | 493 | 676 |
| Row 13 | 180 | 740 | 22.5 | 600 | 798 |
| Row 14 | 200 | 900 | 27.5 | 716 | 924 |
| Row 15 | 250 | 1390 | 41.7 | 1050 | 1250 |
| Row 16 | 300 | 1600 | 57 | 1450 | 1601 |

Now, use the built-in Interpolate1 function in EES to interpolate the Th. expansion values for a given material against temp.

Note that in the EES Procedures below, we have written Th. expansion values between any two given temps TL and TH, since it is more useful to calculate the thermal expansion (or contraction) between those two temps.

See the EES Procedures and examples given below:

---

PROCEDURE DeltaLbyL_BeCu(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for BeCu in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

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{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

IF (TH > 300) or (TL < 0) THEN

CALL ERROR('TL, TH must be between 0 and 300 K !')

ENDIF

DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'BeCu', Temp = TH)*10^(-5)

DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'BeCu', Temp = TL)*10^(-5)

DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL

END

"Example:"

TL = 77 "K"

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TH = 300 "K"

CALL DeltaLbyL_BeCu(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

$DLbyL_{atTH}$ = 0.00329 $DLbyL_{atTL}$ = 0.000176 $DLbyL_{at,TL,TH}$ = 0.003114

TH = 300 [K] TL = 77 [K]

"============================================================"

PROCEDURE DeltaLbyL_AL(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for Aluminum in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

IF (TH > 300) or (TL < 0) THEN

CALL ERROR('TL, TH must be between 0 and 300 K !')

ENDIF

DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'Aluminum', Temp = TH)*10^(-5)

DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'Aluminum', Temp = TL)*10^(-5)

DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

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CALL DeltaLbyL_AL(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

$DLbyL_{atTH}$ = 0.00431 $DLbyL_{atTL}$ = 0.000216 $DLbyL_{at,TL,TH}$ = 0.004094

TH = 300 [K] TL = 77 [K]

"============================================================"

PROCEDURE DeltaLbyL_Steel1020(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for Steel1020 in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

IF (TH > 300) or (TL < 0) THEN

CALL ERROR('TL, TH must be between 0 and 300 K !')

ENDIF

DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'Steel1020', Temp = TH)*10^(-5)

DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'Steel1020', Temp = TL)*10^(-5)

DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

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CALL DeltaLbyL_Steel1020(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

$DLbyL_{atTH}$ = 0.0021 $DLbyL_{atTL}$ = 0.000091 $DLbyL_{at,TL,TH}$ = 0.002009

TH = 300 [K] TL = 77 [K]

"============================================================"

PROCEDURE DeltaLbyL_SS304(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for SS304 in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

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```
IF (TH > 300) or (TL < 0) THEN
    CALL ERROR('TL, TH must be between 0 and 300 K !')
ENDIF
DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'SS304', Temp = TH)*10^(-5)
DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'SS304', Temp = TL)*10^(-5)
DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL
END
```

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL DeltaLbyL_SS304(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $DLbyL_{atTH}$ = 0.00307 | $DLbyL_{atTL}$ = 0.000152 | $DLbyL_{at,TL,TH}$ = 0.002918 |
| TH = 300 [K] | TL = 77 [K] | |

"============================================================"

PROCEDURE DeltaLbyL_Monel(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for Monel in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

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```
IF (TH > 300) or (TL < 0) THEN
    CALL ERROR('TL, TH must be between 0 and 300 K !')
ENDIF
DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'Monel', Temp = TH)*10^(-5)
DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'Monel', Temp = TL)*10^(-5)
DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL
END
```

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL DeltaLbyL_Monel(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $DLbyL_{atTH} = 0.00261$ | $DLbyL_{atTL} = 0.000135$ | $DLbyL_{at,TL,TH} = 0.002475$ |
| TH = 300 [K] | TL = 77 [K] | |

"============================================================"

PROCEDURE DeltaLbyL_Invar(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for Invar in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

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```
IF (TH > 300) or (TL < 0) THEN
    CALL ERROR('TL, TH must be between 0 and 300 K !')
ENDIF
DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'Invar', Temp = TH)*10^(-5)
DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'Invar', Temp = TL)*10^(-5)
DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL
END
```

"Example:"

TL = 77 "K"

TH = 300 "K"

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CALL DeltaLbyL_Invar(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

$DLbyL_{atTH}$ = 0.00054 $DLbyL_{atTL}$ = 0.000017 $DLbyL_{at,TL,TH}$ = 0.000523

TH = 300 [K] TL = 77 [K]

"============================================================="

PROCEDURE DeltaLbyL_Teflon(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for Teflon in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

IF (TH > 300) or (TL < 0) THEN

CALL ERROR('TL, TH must be between 0 and 300 K !')

ENDIF

DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'Teflon', Temp = TH)*10^(-5)

DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'Teflon', Temp = TL)*10^(-5)

DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL DeltaLbyL_Teflon(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

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We get:

**Unit Settings: SI K kPa kJ mass deg**

$DLbyL_{atTH}$ = 0.016 $DLbyL_{atTL}$ = 0.001998 $DLbyL_{at,TL,TH}$ = 0.014

TH = 300 [K] TL = 77 [K]

"============================================================"

PROCEDURE DeltaLbyL_Pyrex(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for Pyrex in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

IF (TH > 300) or (TL < 0) THEN

CALL ERROR('TL, TH must be between 0 and 300 K !')

ENDIF

DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'Pyrex', Temp = TH)*10^(-5)

DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'Pyrex', Temp = TL)*10^(-5)

DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL DeltaLbyL_Pyrex(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

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**Unit Settings: SI K kPa kJ mass deg**

$DLbyL_{atTH}$ = 0.00057 $DLbyL_{atTL}$ = 0.0000052 $DLbyL_{at,TL,TH}$ = 0.0005648

TH = 300 [K] TL = 77 [K]

"============================================================"

PROCEDURE DeltaLbyL_Nylon(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for Nylon in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

IF (TH > 300) or (TL < 0) THEN

CALL ERROR('TL, TH must be between 0 and 300 K !')

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ENDIF

DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'Nylon', Temp = TH)*10^(-5)

DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'Nylon', Temp = TL)*10^(-5)

DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL DeltaLbyL_Nylon(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $DLbyL_{atTH} = 0.0145$ | $DLbyL_{atTL} = 0.001324$ | $DLbyL_{at,TL,TH} = 0.01318$ |
| TH = 300 [K] | TL = 77 [K] | |

"============================================================"

PROCEDURE DeltaLbyL_Polystyrene(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

"(DeltaL / L) * 10^5 for Polystyrene in temp range0 - 300 K.. from Table in Barron... Lookup Table in EES-linear interpolation.

T in K, Multiply the Table value of DeltaL/ L by 10^(-5)"

{ Finds (DeltaL / L). in the range: T = 0 - 300 K:}

IF (TH > 300) or (TL < 0) THEN

CALL ERROR('TL, TH must be between 0 and 300 K !')

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ENDIF

DLbyL_atTH = interpolate1('DELTALbyLE05', 'Temp', 'Polystyrene', Temp = TH)*10^(-5)

DLbyL_atTL = interpolate1('DELTALbyLE05', 'Temp', 'Polystyrene', Temp = TL)*10^(-5)

DLbyL_at_TL_TH = DLbyL_atTH - DLbyL_atTL

END

"Example:"

TL = 77 "K"

TH = 300 "K"

CALL DeltaLbyL_Polystyrene(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

We get:

**Unit Settings: SI K kPa kJ mass deg**

$DLbyL_{atTH}$ = 0.01601 $DLbyL_{atTL}$ = 0.002282 $DLbyL_{at,TL,TH}$ = 0.01373

TH = 300 [K] TL = 77 [K]

"============================================================"

## PROB. V-B.10

**THE FILL-AND DRAIN LINE IN A LIQUID OXYGEN VESSEL IS A 100-MM NOMINAL (4 IN. NOMINAL) STAINLESS-STEEL PIPE. THE DESIGN PRESSURE OF THE VESSEL IS 860 KPA (ABSOLUTE) OR 124.7 PSIA, AND THE LINE PASSES THROUGH THE VACUUM SPACE FOR A DISTANCE OF 7.50 M (24.6 FT). THE WARM END OF THE LINE IS AT 300 K (540°R) AND THE COLD END IS AT 90 K (162°R), AND NO BOILING-CONDENSATION TAKES PLACE WITHIN THE LINE. DETERMINE: (A) THE MINIMUM, THICKNESS AND SCHEDULE NUMBER REQUIRED; AND (B) THE HEAT CONDUCTED DOWN THE LINE TO THE INNER VESSEL [1].**

**Solution:**

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**For thickness of the pipe subjected to internal pressure, we have:**

D_o = 114.3 "mm"

p = 860 "kPa"

s_a = 129200 "kPa for SS 304 .... from Table 6.1"

"then, thickness is given by:"

t = p * D_o / (2 * s_a + 0.8 * p)

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

$D_o$ = 114.3 [mm] p = 860 [kPa] $s_a$ = 129200 [kPa] t = 0.3794 [mm]

We get: thickness required = 0.3794 mm.

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**But, 100 mm nominal pipe, Sch. 5 has a thickness of 2.1 mm. So, adopt Sch. 5 pipe.**

---

**Heat conducted down the line length of 7.5 m, from 300 K to 90 K:**

L = 7.5 "m"

Di = 114.3 - 2 * 2.1 "mm"

A = (pi * (Do^2 - Di^2)/4 ) * 10^(-6) "m^2"

**"Therefore, heat transferred is:**

Q1 = (Kh - Kc) * (A/L) where Q = W, and, K = W/m for the selected material i.e. SS 304"

**"From Table 6.7, we have, for SS 304: Kh = 3060 W/m at 300 K, and Kc = 436 W/m at 90 K"**

Kh = 3060 "W/m"

Kc = 436 "W/m"

"Then:"

Q1 = (Kh - Kc) * (A / L) "W"

**We get Q1 = 0.259 W ... Ans.**

"============================================================"

---

**Alternatively:**

**Use the EES Procedure written earlier for thermal conductivity integral of SS304:**

TL = 90 "K"

TH = 300 "K"

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CALL k_t_Integral_SS304( TL, TH:Integral_at_TL, Integral_at_TH, Integral_TL_TH)

"And:"

Q1 = (A / L) * Integral_TL_TH "W "

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $A = 0.0007402$ [$m^2$] | $D_i = 110.1$ | $D_o = 114.3$ [mm] |
| $Integral_{at,TH} = 3060$ [W/m] | $Integral_{at,TL} = 436$ [W/m] | $Integral_{TL,TH} = 2624$ [W/m] |
| $L = 7.5$ [m] | $p = 860$ [kPa] | $Q1 = 0.259$ [W] |
| $s_a = 129200$ [kPa] | $t = 0.3794$ [mm] | $TH = 300$ [K] |
| $TL = 90$ [K] | | |

**We get: Q1 = 0.259 W ... Ans.**

"============================================================"

## PROB. V-B.11

**USING THE SATURATION RULE, DETERMINE THE PRESSURIZATION MASS REQUIREMENT FOR A 135 M3 (35,660 GAL U.S.) LIQUID-NITROGEN STORAGE VESSEL WITH 10 PERCENT ULLAGE VOLUME. THE TRANSFER RATE IS 45 DM3/S (713 GAL/MIN). THE VESSEL MUST BE MAINTAINED AT 450 KPA (ABSOLUTE) OR 65.3 PSIA DURING A 20-MINUTE TRANSFER PERIOD. ASSUME THAT THE VESSEL CONTAINS 135 M^3 OF LIQUID NITROGEN AT 101.3 KPA (1 ATM) INITIALLY, IS SUDDENLY PRESSURIZED, AND TRANSFER IS CARRIED OUT. [1]**

**Solution:**

"We have, from the saturation rule, for pressurization mass requirement:

DELTAm_g = V2 * rho_g2 - V1 * rho_g1 where

V1 = initial ullage volume

V2 = final ullage volume

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rho_g1 = sat. vapor density at the initial pressure

rho_g2 = sat. vapor density at the final pressure "

V1 = 135 * 0.1 "m^3"

"Vol. transferred from the tank in 20 minutes:"

volume_trans= 45 * 60 * 20 * 10^(-3) "m^3... since volume transferred at a rate of 45 lit/s"

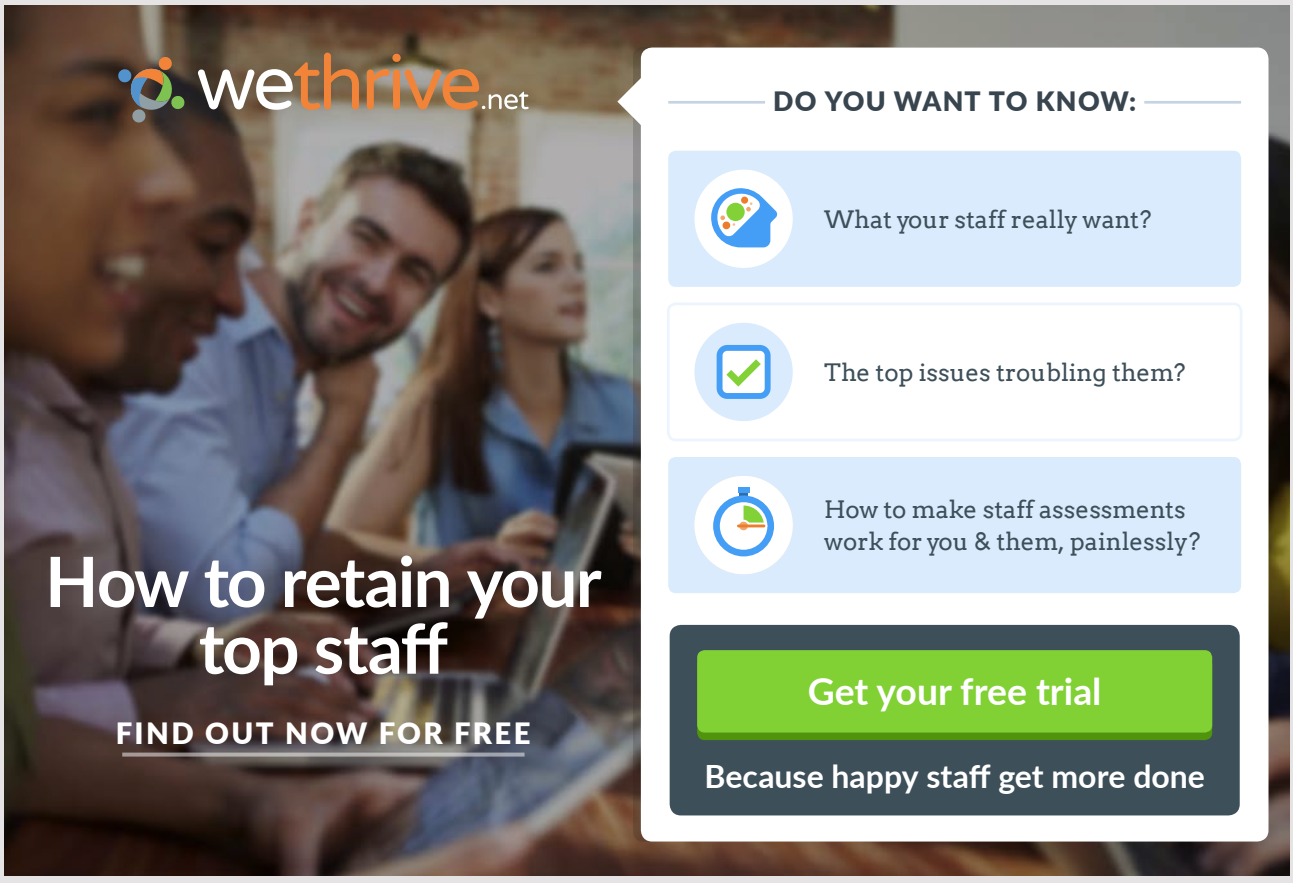
"Therefore, final ullage volume, V2:"

V2 = V1 + volume_trans "m^3"

---

P1 = 101.3 "kPa .... initial pressure"

P2 = 450 "kpa ... final pressure"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**"Then, find out sat. vapour densities at initial and final pressures:"**

"Use the built-in functions of EES:"

x = 1"..for sat. vapor"

rho_g1=Density(Nitrogen,P=P1,x=x) "kg/m^3"

rho_g2=Density(Nitrogen,P=P2,x=x) "kg/m^3"

"Therefore:"

DELTAm_g = V2 * rho_g2 - V1 * rho_g1"kg"

We get:

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $\Delta m_g = 1196$ [kg] | P1 = 101.3 [kPa] | P2 = 450 [kPa] |
| $\rho_{g1} = 4.611$ [kg/m$^3$] | $\rho_{g2} = 18.65$ [kg/m$^3$] | V1 = 13.5 [m$^3$] |
| V2 = 67.5 [m$^3$] | $volume_{trans} = 54$ [m$^3$] | x = 1 |

**We get: DELTAm_g = 1196 kg ... Ans.**

"============================================================"

## PROB.V-B.12

**A SAFETY VALVE FOR NITROGEN SERVICE HAS A FREE AREA OF 30 CM^2 AND A DISCHARGE COEFFICIENT OF 0.650. THE NITROGEN (SPECIFIC-HEAT RATIO = 1.40) ENTERS THE VALVE AT 250 K (450°R) AND 450 KPA ABSOLUTE (65.3 PSIA). DETERMINE THE CAPACITY OF THE VALVE.[1]**

**Solution:**

---

"Required size of safety valve is determined from:

A_v = (m_dot_g * (R_u * T /M)^1/2 ) / ( C * K_D * p_max)

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where:

A_v = discharge area of the valve

m_dot_g = max. mass flow rate through valve

R_u = universal gas const.= 8.314 kJ/kmol.K

T = abs. temp. of the gas at the inlet to valve

M = mol. wt. of the gas flowing through valve = 28.013 kg/kmol

K_D = discharge coeff. determined by test

p_max = (set gauge pressure) * 1.1 + atm. pressure

C = (gamma * (2/ (gamma + 1))^((gamma + 1)/(gamma -1)))^(1/2)

gamma = cp / cv "

---

R_u = 8.314 "kJ/kmol.K"

M = 28.013 "kg/kmol"

K_D = 0.65 "...discharge coeff."

T = 250 "K"

p_max = (450 - 101.3) * 1.1 + 101.3 "kPa"

gamma = 1.4 " = cp/cv"

A_v = 30 * 10^(-4) "m^2"

C = (gamma * (2/ (gamma + 1))^((gamma + 1)/(gamma -1)))^(1/2)

"Now, the required area of the safety valve is given by:"

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A_v = (m_dot_g * (R_u * T /M)^(1/2) ) / ( C * K_D * p_max) "...this eqn determines m_dot_g"

We get:

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $A_v$ = 0.003 [$m^2$] | C = 0.6847 | $\gamma$ = 1.4 |
| $K_D$ = 0.65 | M = 28.01 [kg/kmol] | $\dot{m}_g$ = 0.07516 [kg/s] |
| $p_{max}$ = 484.9 [kPa] | $R_u$ = 8.314 [kJ/kmol.K] | T = 250 [K] |

**i.e. We get: m_dot_g = 0.07516 kg/s ... Ans.**

---

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## PROB.V-B.13.

**A CYLINDRICAL LIQUID-NITROGEN VESSEL IS INSULATED WITH PERLITE ($k_T$ = 1.50mW/m-K -= 8.67 x $10^{-4}$ Btu/hr-ft-°F). THE INNER-VESSEL OUTSIDE DIAMETER IS 1.842m (72.5 IN.), AND THE OUTER-VESSEL INSIDE DIAMETER IS 2.450 M (96.5 IN.). BOTH VESSELS HAVE 2:1 ELLIPTICAL HEADS. THE CYLINDRICAL PORTIONS OF THE VESSEL HAVE LENGTHS AS FOLLOWS: INNER VESSEL, 24 M (78.74 FT); OUTER VESSEL, 24.8 M (81.36 FT). THE OUTER VESSEL TEMPERATURE IS 300 K (540°R), AND THE INNER-VESSEL TEMPERATURE IS 77.8 K (140°R). DETERMINE THE HEAT-TRANSFER RATE THROUGH THE INSULATION.[1]**

**Solution:**

---

"For cyl. vessel"

D_1 = 1.842 "m.... OD of inner vessel"

D_2 = 2.45 "m .... ID of inner vessel"

L_1 = 24 "m .... length of inner vessel"

L_2 = 24.8 "m .... length of outer vessel"

T_1 = 77.8 "K ... temp of inner vessel"

T_2 = 300 "K ... temp of outer vessel"

"Elliptica heads, 2:1 for both inner and outer vessels"

k_t = 1.5 * 10^(-3) "W/m.K ... thermal cond. of perlite insulation"

**Note:** for elliptical heads, outside surface area of the head = 0.345. $\pi$ . $D_o^2$ (from Table 6.3)

And, dish height is given by: ( Ref: https://www.slideshare.net/ajaytyouharia/cedppt )

DH = $D_i$ / 4 (see the fig below):

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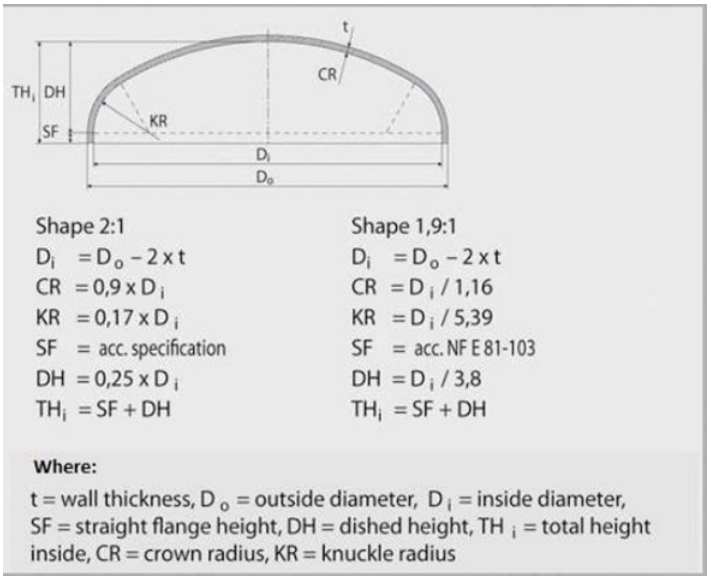
t
CR
TH$_i$
DH
SF
KR
D$_i$
D$_o$
Shape 2:1
D$_i$ = D$_o$ – 2 x t
CR = 0,9 x D$_i$
KR = 0,17 x D$_i$
SF = acc. specification
DH = 0,25 x D$_i$
TH$_i$ = SF + DH
Shape 1,9:1
D$_i$ = D$_o$ – 2 x t
CR = D$_i$ / 1,16
KR = D$_i$ / 5,39
SF = acc. NF E 81-103
DH = D$_i$ / 3,8
TH$_i$ = SF + DH
Where:
t = wall thickness, D$_o$ = outside diameter, D$_i$ = inside diameter,
SF = straight flange height, DH = dished height, TH$_i$ = total height
inside, CR = crown radius, KR = knuckle radius

---

A_1 = pi * D_1 * L_1 "m^2 .... surface area of inner vessel"

A_2 = pi * D_2 * L_2 "m^2 ... surface area of outer vessel"

"Therefore, mean area of insulation around the inner shell:"

A_m = (A_2 -A_1) / ln (A_2 / A_1)

"Thickness of insulation around the shell is:"

DELTAx = (D_2 - D_1) / 2 "m"

"Therefore, heat transfer rate through insulation of the cylindrical portion is:"

Q_cyl = k_t * A_m * (T_2 - T_1) / DELTAx "W... for cyl part"

"For Elliptical heads, total area of two inner cyl heads:"

A_innerheads = 2 * (0.345 * pi * D_1^2) "m^2"

"Similarly, total area of two outer heads:"

A_outerheads = 2 * (0.345 * pi * D_2^2) "m^2"

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"Mean surface area between the heads is:"

A_mean = (A_innerheads * A_outerheads)^(1/2) "m^2"

"Thickness of insulation around the heads is:"

DELTAx_insheads = ( D_2 - D_1 ) / 4 "..m...since dish height for 2:1 elliptical heads is D/4"

"Therefore, heat transfer rate through insulation around the heads is:"

Q_heads = k_t * A_mean * (T_2 - T_1) / DELTAx_insheads "W"

"Therefore, total heat transfer rate through insulation:"

Q_tot = Q_cyl + Q_heads "W ... total heat transfer rate through insulation"

**And, we get:**

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**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $A_1 = 138.9$ [m$^2$] | $A_2 = 190.9$ [m$^2$] | $A_{innerheads} = 7.355$ [m$^2$] |
| $A_m = 163.5$ [m$^2$] | $A_{mean} = 9.783$ [m$^2$] | $A_{outerheads} = 13.01$ [m$^2$] |
| $\Delta x = 0.304$ [m] | $\Delta x_{insheads} = 0.152$ [m] | $D_1 = 1.842$ [m] |
| $D_2 = 2.45$ [m] | $k_t = 0.0015$ [W/m.K] | $L_1 = 24$ [m] |
| $L_2 = 24.8$ [m] | $Q_{cyl} = 179.3$ [W] | $Q_{heads} = 21.45$ [W] |
| $Q_{tot} = 200.7$ [W] | $T_1 = 77.8$ [K] | $T_2 = 300$ [K] |

**Thus, heat transfer through insulation only for Cylinder, heads, and total is:**

**Q_cyl = 179.3 W; Q_heads = 21.45 W, and Q_tot = 200.7 W .... Ans.**

---

## PROB.V-B.14.

### WRITE AN EES PROCEDURE FOR TOTAL HEAT TRANSFER THROUGH THE INSULATION, Q_INS FOR A CYLINDRICAL DEWAR, WITH ELLIPTICAL HEADS.

PROCEDURE Q_ins_tot_cyl_elliptheads(D_1, D_2, L_1, L_2, T_1, T_2, k_t : A_1, A_2, A_m, Q_cyl, A_innerheads, A_outerheads, A_m_heads, Q_heads, Q_tot)

{Finds the heat transfer through insulation (foam, evacuated powder) only, for a cylindrical dewar, with elliptical heads'

Inputs: D_1, D_2, L_1, L_2, T_1, T_2 and k_t.

Outputs: A_1, A_2, A_m, Q_cyl, A_innerheads, A_outerheads, A_M_heads, Q_heads, and Q_tot }

A_1 = pi * D_1 * L_1 "m^2 .... surface area of inner vessel"

A_2 = pi * D_2 * L_2 "m^2 ... surface area of outer vessel"

"Therefore, mean area of insulation around the inner shell:"

A_m = (A_2 -A_1) / ln (A_2 / A_1)

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"Thickness of insulation around the shell is:"

DELTAx = (D_2 - D_1) / 2 "m"

"Therefore, heat transfer rate through insulation of the cylindrical portion is:"

Q_cyl = k_t * A_m * (T_2 - T_1) / DELTAx "W... for cyl part"

"For Elliptical heads, total area of two inner cyl heads:"

A_innerheads = 2 * (0.345 * pi * D_1^2) "m^2"

"Similarly, total area of two outer heads:"

A_outerheads = 2 * (0.345 * pi * D_2^2) "m^2"

"Mean surface area between the heads is:"

A_m_heads = (A_innerheads * A_outerheads)^(1/2) "m^2"

"Thickness of insulation around the heads is:"

DELTAx_insheads = ( D_2 - D_1 ) / 4 "..m...since dish height for 2:1 elliptical heads is D/4"

"Therefore, heat transfer rate through insulation around the heads is:"

Q_heads = k_t * A_m_heads * (T_2 - T_1) / DELTAx_insheads "W"

"Therefore, total heat transfer rate through insulation:"

Q_tot = Q_cyl + Q_heads "W ... total heat transfer rate through insulation"

END

"============================================================"

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## PROB.V-B.15

**SOLVE PROB. V-B.13 USING THE EES PROCEDURE WRITTEN ABOVE:**

**Solution:**

**Let us write the data:**

D_1 = 1.842 "m.... OD of inner vessel"; D_2 = 2.45 "m .... ID of inner vessel";

L_1 = 24 "m .... length of inner vessel"; L_2 = 24.8 "m .... length of outer vessel";

T_1 = 77.8 "K ... temp of inner vessel"; T_2 = 300 "K ... temp of outer vessel";

"Elliptica heads, 2:1 for both inner and outer vessels"; k_t = 1.5 * 10^(-3) "W/m.K ... thermal cond. of perlite insulation";

**Now, applying the EES Procedure:**

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CALL Q_ins_tot_cyl_elliptheads(D_1, D_2, L_1, L_2, T_1, T_2, k_t : A_1, A_2, A_m, Q_cyl, A_innerheads, A_outerheads, A_m_heads, Q_heads, Q_tot)

**And, we get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $A_1 = 138.9$ [m$^2$] | $A_2 = 190.9$ [m$^2$] | $A_{innerheads} = 7.355$ [m$^2$] |
| $A_m = 163.5$ [m$^2$] | $A_{m,heads} = 9.783$ [m$^2$] | $A_{outerheads} = 13.01$ [m$^2$] |
| $D_1 = 1.842$ [m] | $D_2 = 2.45$ [m] | $k_t = 0.0015$ [W/m.K] |
| $L_1 = 24$ [m] | $L_2 = 24.8$ [m] | $Q_{cyl} = 179.3$ [W] |
| $Q_{heads} = 21.45$ [W] | $Q_{tot} = 200.7$ [W] | $T_1 = 77.8$ [K] |
| $T_2 = 300$ [K] | | |

**Thus, heat transfer through insulation only for Cylinder, heads, and total is:**

**Q_cyl = 179.3 W; Q_heads = 21.45 W, and Q_tot = 200.7 W .... Ans.**

**i.e. the values are the same as obtained earlier.**

---

## PROB.V-B.16.

### WRITE A EES FUNCTION TO CALCULATE HEAT TRANSFER THROUGH INSULATION ONLY, FOR A CYLINDRICAL TANK WITH HEMISPHERICAL ENDS.

{Finds the heat transfer through insulation (foam, evacuated powder) only, for a cylindrical dewar, with hemispherical heads'

Inputs: D_1, D_2, L_1, L_2, T_1, T_2 and k_t.

Outputs: A_1, A_2, A_m, Q_cyl, A_innerheads, A_outerheads, A_M_heads, Q_heads, and Q_tot }

A_1 = pi * D_1 * L_1 "m^2 .... surface area of inner vessel"

A_2 = pi * D_2 * L_2 "m^2 ... surface area of outer vessel"

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"Therefore, mean area of insulation around the inner shell:"

A_m = (A_2 -A_1) / ln (A_2 / A_1)

"Thickness of insulation around the shell is:"

DELTAx = (D_2 - D_1) / 2 "m"

"Therefore, heat transfer rate through insulation of the cylindrical portion is:"

Q_cyl = k_t * A_m * (T_2 - T_1) / DELTAx "W... for cyl part"

"For hemispherical heads, total area of two inner cyl heads:"

A_innerheads = 2 * ( pi * D_1^2) / 2 "m^2"

"Similarly, total area of two outer heads:"

A_outerheads = 2 * ( pi * D_2^2) / 2 "m^2"

"Mean surface area between the heads is:"

A_m_heads = (A_innerheads * A_outerheads)^(1/2) "m^2"

"Thickness of insulation around the heads is:"

DELTAx_insheads = ( D_2 - D_1 ) / 2 " m."

"Therefore, heat transfer rate through insulation around the heads is:"

Q_heads = k_t * A_m_heads * (T_2 - T_1) / DELTAx_insheads "W"

"Therefore, total heat transfer rate through insulation:"

Q_tot = Q_cyl + Q_heads "W ... total heat transfer rate through insulation"

END

"============================================================"

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## PROB.V-B.17

**DETERMINE THE HEAT TRANSFER THROUGH THE INSULATION FOR A 106 M3 (28 000 GAL U.S.) LIQUID-OXYGEN STORAGE VESSEL WITH THE FOLLOWING CHARACTERISTICS. THE INSULATION IS EVACUATED PERLITE WITH AN APPARENT THERMAL CONDUCTIVITY OF 1.20 mW/m-K (0.69 X $10^{-3}$ BTU/HR-FT-°F). THE INNER SHELL HAS AN OD OF 3.070 M AND A LENGTH OF 14.0 M, AND THE INNER-VESSEL HEMISPHERICAL HEADS HAVE AN OD OF 3.062 M. THE OUTER SHELL HAS AN ID OF 3.636 M AND A LENGTH OF 14.0 M, AND THE OUTER-VESSEL HEMISPHERICAL HEADS HAVE AN ID OF 3.648 M. THE TEMPERATURE OF THE OUTER VESSEL MAY BE ASSUMED TO BE 300 K, AND THE TEMPERATURE OF THE INNER VESSEL MAY BE ASSUMED TO BE 90.2 K.[1]**

**Solution:**

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Above problem is part of a worked-out problem in Ref.[1]. Shown here to illustrate the use of the above EES Procedure and compare it with the results in Ref.[1]

**Note** The simple EES Procedure above, does not take in to account the thickness of the plates; still, the results match very well.

**Let us write the data:**

---

D_1 = 3.07 "m.... OD of inner vessel"; D_2 = 3.636 "m .... ID of inner vessel";

L_1 = 14 "m .... length of inner vessel"; L_2 = 14 "m .... length of outer vessel";

T_1 = 90.2 "K ... temp of inner vessel"; T_2 = 300 "K ... temp of outer vessel";

"Hemispherical heads," k_t = 1.2 * 10^(-3) "W/m.K ... thermal cond. of perlite insulation";

**Now, apply the EES Procedure:**

---

CALL Q_ins_tot_cyl_hemisphheads(D_1, D_2, L_1, L_2, T_1, T_2, k_t : A_1, A_2, A_m, Q_cyl, A_innerheads, A_outerheads, A_m_heads, Q_heads, Q_tot)

**And, we get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $A_1 = 135$ [m²] | $A_2 = 159.9$ [m²] | $A_{innerheads} = 29.61$ [m²] |
| $A_m = 147.1$ [m²] | $A_{m,heads} = 35.07$ [m²] | $A_{outerheads} = 41.53$ [m²] |
| $D_1 = 3.07$ [m] | $D_2 = 3.636$ [m] | $k_t = 0.0012$ [W/m.K] |
| $L_1 = 14$ [m] | $L_2 = 14$ [m] | $Q_{cyl} = 130.9$ [W] |
| $Q_{heads} = 31.2$ [W] | $Q_{tot} = 162.1$ [W] | $T_1 = 90.2$ [K] |
| $T_2 = 300$ [K] | | |

**i.e.**

**Heat transfer rate in insulation in cylindrical part = Qcyl = 130.9 W,**

**Heat transfer rate in insulation in hemispherical heads = Qheads = 31.2 W, and**

**Total heat transfer through insulation alone, Qtot = Qcyl + Qheads = 162.1 W**

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**Now, comparing to the above results from the EES Procedure, to the results in Ref.[1], corresponding values are: 130.881, 31.197, 162.078 W….i.e. they match well.**

"============================================================="

## PROB.V-B.18

### WRITE AN EES PROCEDURE TO DETERMINE HEAT TRANSFER RATE IN A VACUUM INSULATED SPHERICAL DEWAR. ALSO, INCLUDE THE HEAT TRANSFER BY GAS CONDUCTION.

**Solution:**

---

PROCEDURE Q_ins_vacuum_sphere(D_1, D_2, T_1, T_2, e1, a1, e2, a2, p, R_gas, gamma, mu_gas : A_1, A_2,F_e, Q_rad, mfp, DELTAx, F_a, G, Q_gas, Q_tot)

{Finds the heat transfer through vacuum insulation for a spherical dewar; Also includes heat transfer by residual gas conduction.}

"Inputs:

D_1 = OD of inner vessel, m; D_2 = ID of outer vessel, m

T_1 = temp of inner vessel, K; T_2 = temp of outer vessel, K

a1 = accommodation coeff for air at temp T_1; a2 = accommodation coeff for air at temp T_2

e1 = emissivity of inner vessel; e2 = emissivity of outer vessel

p = pressure, Pa; R_gas = gas constant for the gas (i.e. air), J/kg.K

gamma = cp/cv = sp.heat ratio for gas; μ_gas = viscosity of gas at temp T_2, Pa-s "

"Outputs: as defined below."

A_1 = pi * D_1^2 "m^2 ... surface area of inner sphere"

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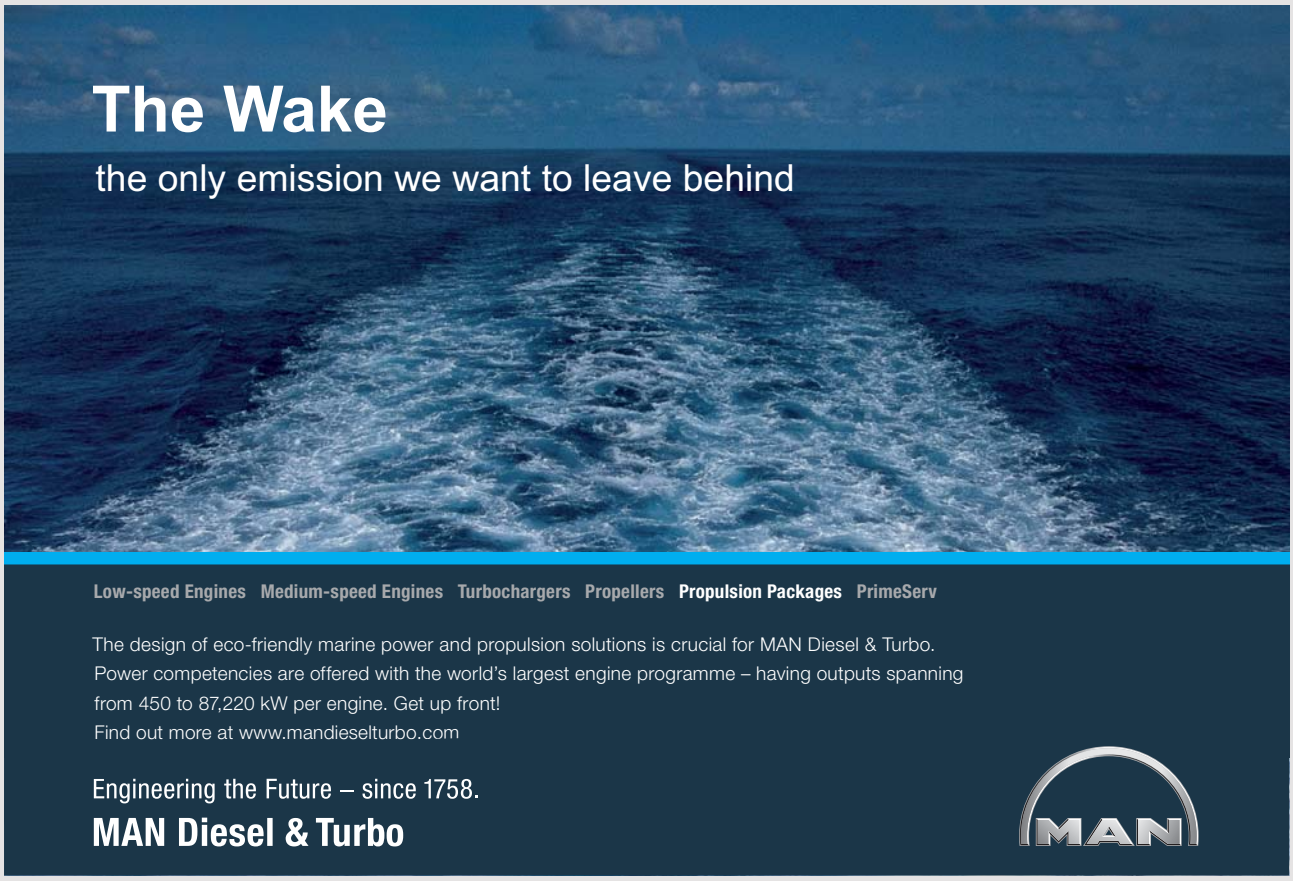
```
A_2 = pi * D_2^2 "m^2 ... surface area of outer sphere"

F_12 = 1"configuration factor"

F_e = 1 / ( 1/e1 + (A_1 / A_2) * (1/e2 - 1)) "...emissivity factor"

sigma = 5.669 * 10^(-8) "W/m^2.K^4.... Stefan - Boltzmann const."

Q_rad = F_e * F_12 * sigma * A_1 * (T_2^4 - T_1^4) "W ... radiation heat loss"

mfp = (mu_gas / p) * (pi * R_gas * T_2 / 2)^(1/2) " m ... mean free path of gas molecules"

DELTAx = (D_2 - D_1) / 2 "m ... distance between surfaces"

IF (mfp < DELTAx) THEN Q_gas = 0 "W ...gas conduction"

IF (mfp > DELTAx) THEN

    F_a = 1 / (1 / a1 + (A_1 / A_2) * (1/a2 - 1)) "...accommodation coefficient factor"
```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```
    G = ((gamma + 1) / (gamma - 1)) * (R_gas /( 8 * pi * T_2))^(1/2) * F_a

    Q_gas = G * p * A_1 * (T_2 - T_1) "W ... gas conduction"

ENDIF

Q_tot = Q_rad + Q_gas " W ... total heat loss"

END

"============================================================="
```

**Now, let us solve a problem using the above Function.**

This is a worked-out problem in Barron, Ref.[1]. Solved with this EES Procedure, just to illustrate the use of this Procedure:

---

## PROB.V-B.19

**DETERMINE THE TOTAL HEAT-TRANSFER RATE FROM THE OUTER SHELL TO THE INNER SHELL OF A SPHERICAL DEWAR WITH A 1.50 M (59 IN.) OD INNER SHELL AND A 2.10 M (83 IN.) ID OUTER SHELL. THE OUTER SHELL IS AT 300 K (540°R); IT HAS AN EMISSIVITY OF 0.10 AND AN ACCOMMODATION COEFFICIENT OF 0.90. THE INNER SHELL IS AT 78 K (140°R); IT HAS AN EMISSIVITY OF 0.05 AND AN ACCOMMODATION COFFICIENT OF 1.00. THE GAS WITHIN THE ANNULAR SPACE IS AIR AT A PRESSURE OF 2 MPA (1.5 X $10^{-5}$ TORR) MEASURED AT 300 K. THE DEWAR IS INSULATED BY VACUUM ALONE.[1]**

```
D_1 = 1.5 "OD of inner vessel, m"; D_2 = 2.1 " ID of outer vessel, m";

T_1 = 77.8 "temp of inner vessel, K"; T_2 = 300 " temp of outer vessel, K";

a1 = 1 "accommodation coeff for air at temp T_1"; a2 = 0.9 "accommodation coeff for air at temp T_2";

e1 =0.05 " emissivity of inner vessel"; e2 = 0.1 "emissivity of outer vessel";
```

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p = 2 * 10^(-3) "pressure, Pa"; R_gas = 287 "gas constant for the gas (i.e. air), J/kg.K";

gamma = 1.4 "cp/cv = sp.heat ratio for gas"; mu_gas = 18.47 * 10^(-6) " viscosity of gas at temp T_2, Pa-s ";

CALL Q_ins_vacuum_sphere(D_1, D_2, T_1, T_2, e1, a1, e2, a2, p, R_gas, gamma, mu_gas : A_1, A_2,F_e, Q_rad, mfp, DELTAx, F_a, G, Q_gas, Q_tot)

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $a1 = 1$ | $a2 = 0.9$ | $A_1 = 7.069$ [m$^2$] |
| $A_2 = 13.85$ [m$^2$] | $\Delta x = 0.3$ [m] | $D_1 = 1.5$ [m] |
| $D_2 = 2.1$ [m] | $e1 = 0.05$ | $e2 = 0.1$ |
| $F_a = 0.9464$ | $F_e = 0.04066$ | $G = 1.108$ |
| $\gamma = 1.4$ | $mfp = 3.396$ [m] | $\mu_{gas} = 0.00001847$ [Pa.s] |
| $p = 0.002$ [kPa] | $Q_{gas} = 3.480$ [W] | $Q_{rad} = 131.391$ [W] |
| $Q_{tot} = 134.870$ [W] | $R_{gas} = 287$ [J/kg.K] | $T_1 = 77.8$ [K] |
| $T_2 = 300$ [K] | | |

**Thus:**

**Heat transfer rate by radiation = $Q_{rad}$ = 131.391 W**

**Heat transfer by molecular gas conduction = $Q_{gas}$ = 3.48 W, and**

**Total heat transfer, $Q_{tot} = Q_{rad} + Q_{gas}$ = 134.87 W … Ans.**

"============================================================"

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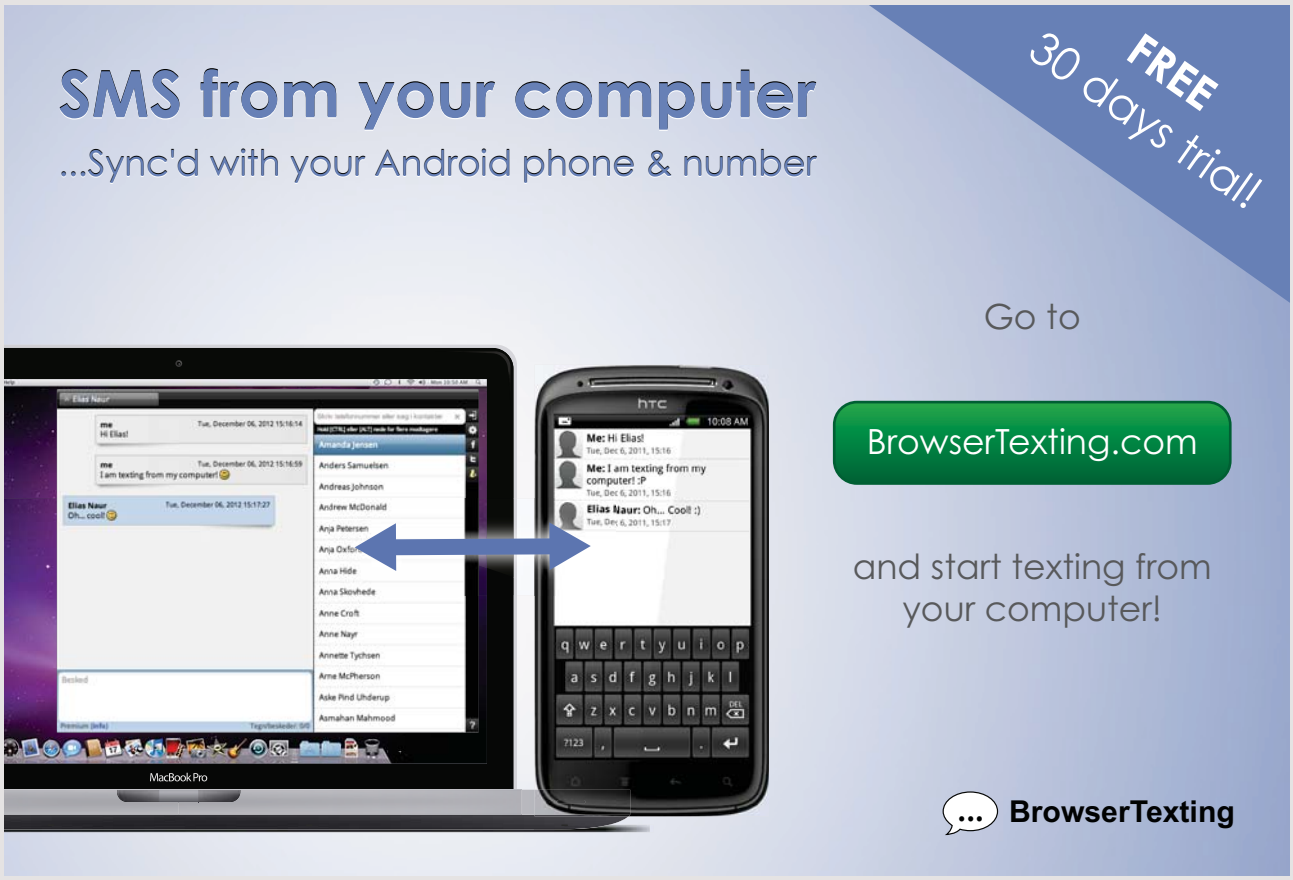
## PROB.V-B.20

**A SPHERICAL LIQUID HYDROGEN VESSEL HAS AN INNER-VESSEL OUTSIDE DIAMETER OF 1.220 M (48 IN.) AND AN OUTER-VESSEL INSIDE DIAMETER OF 1.675 M (66 IN.). THE VESSEL IS INSULATED BY VACUUM ALONE. THE EMISSIVITY OF THE INNER VESSEL IS 0.04, AND THE EMISSIVITY OF THE OUTER VESSEL IS 0.09. THE GAS IN THE VACUUM SPACE IS AIR (R = 287 J /KG-K; $\gamma$ = 1.40) AT A PRESSURE OF 15 mPa (1.1 X $10^{-4}$ TORR). THE OUTER VESSEL TEMPERATURE IS 295 K (531°R), AND THE INNER-VESSEL TEMPERATURE IS 20.5 K (36.9°R). DETERMINE: (A) THE HEAT-TRANSFER RATE BY RADIATION; (B) THE HEAT-TRANSFER RATE BY MOLECULAR CONDUCTION; AND (C) THE RADIATION HEAT-TRANSFER RATE IF AN INTERMEDIATE FLOATING SHIELD HAVING A 1.45-M (57-IN.) DIAMETER AND AN EMISSIVITY ON BOTH SIDES OF 0.05 WERE USED.[1]**

**Solution:**

**We first write the data, and then apply the EES Procedure written above:**

"Data:"L_1 = 1.22 "OD of inner vessel, m"; D_2 = 1.675 " ID of outer vessel, m";

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T_1 = 20.5 "temp of inner vessel, K"; T_2 = 295 " temp of outer vessel, K";

a1 = 1 "accommodation coeff for air at temp T_1";

a2 = 0.9 "accommodation coeff for air at temp T_2";e1 =0.04 " emissivity of inner vessel";

e2 = 0.09 "emissivity of outer vessel";p = 15 * 10^(-3) "pressure, Pa";

R_gas = 287 "gas constant for the gas (i.e. air), J/kg.K";gamma = 1.4 "cp/cv = sp.heat ratio for gas";

mu_gas = 18.47 * 10^(-6) " viscosity of gas at temp T_2, Pa-s ";

CALL Q_ins_vacuum_sphere(D_1, D_2, T_1, T_2, e1, a1, e2, a2, p, R_gas, gamma, mu_gas : A_1, A_2,F_e, Q_rad, mfp, DELTAx, F_a, G, Q_gas, Q_tot)

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $a1 = 1$ | $a2 = 0.9$ | $A_1 = 4.676$ [m$^2$] |
| $A_2 = 8.814$ [m$^2$] | $\Delta x = 0.2275$ [m] | $D_1 = 1.22$ [m] |
| $D_2 = 1.675$ [m] | $e1 = 0.04$ | $e2 = 0.09$ |
| $F_a = 0.9443$ | $F_e = 0.03293$ | $G = 1.115$ |
| $\gamma = 1.4$ | $mfp = 0.449$ [m] | $\mu_{gas} = 0.00001847$ [Pa.s] |
| $p = 0.015$ [kPa] | $Q_{gas} = 21.463$ [W] | $Q_{rad} = 66.114$ [W] |
| $Q_{tot} = 87.577$ [W] | $R_{gas} = 287$ [J/kg.K] | $T_1 = 20.5$ [K] |
| $T_2 = 295$ [K] | | |

**Thus:**

**Heat transfer rate by radiation = $Q_{rad}$ = 66.114 W**

**Heat transfer by molecular gas conduction = $Q_{gas}$ = 21.463 W, and**

**Total heat transfer, $Q_{tot}$ = $Q_{rad}$ + $Q_{gas}$ = 87.577 W … Ans.**

"============================================================"

**If one floating shield is used:**

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**(Ref: Fundamentals of Heat & Mass Transfer, by M.Thirumaleshwar, Publ:Pearson Edu, 2006, ... page 797.)**

**Then, equation for heat transfer in a spherical system, with one shield, is:**

$$Q_{12\_oneshield} = \frac{A_1 \cdot \sigma \cdot \left(T_2^4 - T_1^4\right)}{\frac{1}{e_1} + \frac{A_1}{A_2}\cdot\left(\frac{1}{e_1} - 1\right) + \frac{A_1}{A_3}\cdot\left(\frac{1}{e_{s1}} + \frac{1}{e_{s2}} - 1\right)}$$

where: $A_1$, $A_2$, $A_3$ ... are the surface areas of inner sphere, outer sphere and the radiation shields respectively.

---

**So, we continue the EES program:**

"If one floating shield is used:

(Ref: Fundamentals of Heat & Mass Transfer, by M.Thirumaleshwar, Publ:Pearson Edu, 2006, ... page 797.)"

D_3 = 1.47 "m ... dia of shield"

e_s1 = 0.05; e_s2 = 0.05 "...emissivities of two sides of shield"

sigma = 5.669 * 10^(-8) "W/m^2.K^4 .... Stefan-Boltzmann const."

A_3 = pi * D_3^2 "m^2 .... surface area of shield"

"Therefore:"

Numerator = A_1 * sigma * (T_1^4 - T_2^4)

Denominator = 1 / e1 + (A_1 / A_2) * (1 / e1 - 1) + (A_1 / A_3) * (1 / e_s1 + 1 / e_s2 - 1)

Q_12_oneshield = Numerator / Denominator

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**And, we get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| a1 = 1 | a2 = 0.9 | $A_1$ = 4.676 [$m^2$] |
| $A_2$ = 8.814 [$m^2$] | $A_3$ = 6.789 [$m^2$] | $\Delta x$ = 0.2275 [m] |
| Denominator = 64.59 [-] | $D_1$ = 1.22 [m] | $D_2$ = 1.675 [m] |
| $D_3$ = 1.47 [m] | e1 = 0.04 | e2 = 0.09 |
| $e_{s1}$ = 0.05 | $e_{s2}$ = 0.05 | $F_a$ = 0.9443 |
| $F_e$ = 0.03293 | G = 1.115 | $\gamma$ = 1.4 |
| mfp = 0.449 [m] | $\mu_{gas}$ = 0.00001847 [Pa.s] | Numerator = -2007 [W] |
| p = 0.015 [kPa] | $Q_{12,oneshield}$ = -31.08 [W] | $Q_{gas}$ = 21.463 [W] |
| $Q_{rad}$ = 66.114 [W] | $Q_{tot}$ = 87.577 [W] | $R_{gas}$ = 287 [J/kg.K] |
| $\sigma$ = 5.669E-08 [$W/m^{2.K^4}$] | $T_1$ = 20.5 [K] | $T_2$ = 295 [K] |

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**Thus, we get:**

**Heat transfer rate when one shield is used = Q_12_oneshield = 31.08 W ….Ans.**

**Note: -ve sign in the Results indicates that heat flow is from surface 2 to surface 1, i.e. from outer sphere to the inner sphere. Also, note that by using one shield, the radiation heat transfer is reduced from 66.114 W to 31.08 W.**

"============================================================"

---

## PROB.V-B.21

**DETERMINE THE PRESSURE TO WHICH HYDROGEN GAS (R = 4124 J / KG-K; γ =1.41) MUST BE REDUCED IN ORDER THAT THE HEAT FLUX BY MOLECULAR CONDUCTION THROUGH THE GAS BE LIMITED TO 30 W/ M2 (9.5 BTU/HR-FT). THE TWO SURFACES ENCLOSING THE GAS MAY BE CONSIDERED AS INFINITE PLANES AT TEMPERATURES OF 300 K (540°R) AND 78 K (140°R). THE PRESSURE GAUGE IS AT 300 K.[1]**

**Solution:**

For molecular conduction to occur, the mean free path of gas, i.e. mfp must be greater than the spacing between the plates, Δx:

So, consider 2 parallel plates, with areas A1 and A2, space between them being Δx, and let the pressure be such that mfp > Δx.

---

"Let:"

A_1 = 1 "m^2"; A_2 = 1 "m^2"

T_1 = 78 "K"; T_2 = 300 "K"

"Accommodation coeffs for H2 at 78 K and 300 K: from Table in Ref.[1]"

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**Accommodation coefficients for hydrogen at 300 K and 78 K: (From Table)**

Table 6.10 Approximate accommodation coefficients [1]

| Temperature | | Gas | | | |
|---|---|---|---|---|---|
| K | °R | Helium | Hydrogen | Neon | Air |
| 300 | 540 | 0.29 | 0.29 | 0.66 | 0.8–0.9 |
| 78 | 140 | 0.42 | 0.53 | 0.83 | 1.00 |
| 20 | 36 | 0.59 | 0.97 | 1.00 | 1.00 |

By permission from R. B. Scott, *Cryogenic Engineering*, D. Van Nostrand Co., Princeton, N.J., 1959.

---

a1 = 0.29 "...at 300 K"

a2 = 0.53 "...at 78 K"

R_gas = 4124 "J/kg.K"

gamma = 1.41 "= cp/cv for H2"

Q_gas = 30 "W/m^2 ... by data"

"Then, we have:"

F_a = 1 / (1 / a1 + (A_1 / A_2) * (1/a2 - 1)) "...accommodation coefficient factor"

G = ((gamma + 1) / (gamma - 1)) * (R_gas /( 8 * pi * T_2))^(1/2) * F_a

"And:"

Q_gas = G * p * A_1 * (T_2 - T_1) "W ... gas conduction"

"Note: Above eqn determines p since Q_gas is given as 30 W in data;"

**And, we get:**

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**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| $a1 = 0.29$ | $a2 = 0.53$ | $A_1 = 1$ [$m^2$] | $A_2 = 1$ [$m^2$] |
| $F_a = 0.2307$ | $G = 1.003$ | $\gamma = 1.41$ | $p = 0.1348$ [Pa] |
| $Q_{gas} = 30.000$ [W] | $R_{gas} = 4124$ [J/kg.K] | $T_1 = 78$ [K] | $T_2 = 300$ [K] |

**Thus:**

**Pressure to which hydrogen gas must be reduced in order that the heat flux by molecular conduction through the gas be limited to 30 W/m2 = 0.1348 Pa …Ans.**

"============================================================"

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## PROB. V-B.22

**HEAT IS TRANSFERRED BY MOLECULAR CONDUCTION ACROSS A VACUUM SPACE WITH ONE INTERMEDIATE FLOATING SHIELD. THE PRESSURE OF THE RESIDUAL GAS (HELIUM, R = 2077 J/KG-K; $\gamma$ = 1.667) IS 0.120 PA (9 X $10^{-4}$ TORR) AS MEASURED BY A GAUGE AT 300 K (540°R). THE WARM SURFACE IS AT 300 K (540°R) AND HAS AN ACCOMMODATION COEFFICIENT OF 0.30; THE COLD SURFACE IS AT 22 K (39.6°R) AND HAS AN ACCOMMODATION COEFLICIENT OF 0.60. THE SHIELD MATERIAL HAS AN ACCOMMODATION COEFFICIENT OF 0.40. DETERMINE THE HEAT FLUX BY MOLECULAR CONDUCTION, W/M2, ASSUMING THAT THE SURFACES MAY BE TREATED AS INFINITE PARALLEL PLATES. [1]**

**Solution:**

Consider 2 parallel plates, with areas A1 and A2, space between them being $\Delta x$, and let the pressure be such that mfp > $\Delta x$.

---

"Let:"

A_1 = 1 "m^2"; A_2 = 1 "m^2"

T_1 = 300 "K"; T_2 = 22 "K"

p = 0.12 "Pa"

---

R_gas = 2077 "J/kg.K ... for He"

gamma = 1.667

**"Accommodation coeffs from data:"**

a1 = 0.3 "for He at 300 K"

a2 = 0.6 "for He at 22 K"

a_s = 0.4 "..accommodation coeff for shield"

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**Noting that accommodation coeff factor, $F_a$ has the same form as that of emissivity factor, for parallel plates, we write:**

1/F_a = (1 / a1 + 1 / a_s -1) + (N - 1) * (2 / a_s -1) + ( 1 / a2 + 1/a_s -1) "...when there are N shields between warm and cold plates"

"So, when there is only one shield, we write:"

N = 1

"And:"

G = ((gamma + 1) / (gamma - 1)) * (R_gas /( 8 * pi * T_1))^(1/2) * F_a

"Therefore, heat transfer by molecular gas conduction is given by:"

Q_gas = G * p * A_1 * (T_1 - T_2) "W ... gas conduction"

**When there is only one shield, we write:** N = 1

"And:"G = ((gamma + 1) / (gamma - 1)) * (R_gas /( 8 * pi * T_1))^(1/2) * F_a

"Therefore, heat transfer by molecular gas conduction is given by:"

Q_gas = G * p * A_1 * (T_1 - T_2) "W ... gas conduction"

We get:

**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| a1 = 0.3 | a2 = 0.6 | $A_1$ = 1 [$m^2$] | $A_2$ = 1 [$m^2$] |
| $a_s$ = 0.4 | $F_a$ = 0.125 | G = 0.2623 | $\gamma$ = 1.667 |
| N = 1 | p = 0.12 [Pa] | **$Q_{gas}$ = 8.751** [W] | $R_{gas}$ = 2077 [J/kg.K] |
| $T_1$ = 300 [K] | $T_2$ = 22 [K] | | |

**i.e. We get: Q_gas = 8.751 W... Ans.**

**(b) If the shield were not there, what would be the heat transfer rate ?**

"If there is no radiation shield, F_aa would be:"

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1 / F_aa = 1 / a1 + 1/a2 -1

"And, new G = GG would be:"

GG = ((gamma + 1) / (gamma - 1)) * (R_gas /( 8 * pi * T_1))^(1/2) * F_aa

"And, Q_gas_noshield would be:"

Q_gas_noshield = GG * p * A_1 * (T_1 - T_2) "W ... gas conduction"

**And, we get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| $a1 = 0.3$ | $a2 = 0.6$ | $A_1 = 1$ [$m^2$] | $A_2 = 1$ [$m^2$] |
| $a_s = 0.4$ | $F_a = 0.125$ | $F_{aa} = 0.25$ | $G = 0.2623$ |
| $\gamma = 1.667$ | $GG = 0.5247$ | $N = 1$ | $p = 0.12$ [Pa] |
| $\mathbf{Q_{gas}} = \mathbf{8.751}$ [W] | $Q_{gas,noshield} = 17.5$ [W] | $R_{gas} = 2077$ [J/kg.K] | $T_1 = 300$ [K] |
| $T_2 = 22$ [K] | | | |

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**Therefore, heat transfer by molecular gas conduction when there is no shield is given by:**

**Q_gas_noshield = 17.5 W …. Ans.**

"============================================================"

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## PROB.V-B.23

**DETERMINE THE MEAN APPARENT THERMAL CONDUCTIVITY OF A MULTILAYER INSULATION (A) BETWEEN 300 K (540°R) AND 20.5 K (36.9°R), AND (B) BETWEEN 20.5 K (36.9°R) AND 4.4 K (7.9°R), IF THE INSULATION IS MADE UP OF 25 LAYERS/CM (63.5 LAYERS/IN.) OF ALUMINIUM FOIL (EMISSIVITY = 0.05) AND FIBERGLASS PAPER ($h_c$ = 85 mW/m²-K = 0.015 BTU/HR-FT²-°F).[1]**

**Solution:**

**We have: for a well-evacuated multilayer insulation, apparent thermal conductivity may be calculated from:**

$$k_t = \left[\frac{N}{\Delta x}\right]^{-1} \cdot \left[h_c + \frac{\sigma \cdot e \cdot (T_h^2 + T_c^2) \cdot (T_h + T_c)}{2 - e}\right]$$

**For this problem, we have:**

k_t = (NbyDELTAx)^(-1) * (h_c +(sigma * e * (T_h^2 + T_c^2) * ( T_h + T_c)) / (2 - e))

“where:

h_c = solid conductance for spacer material

---

sigma = Stefan-Boltzmann const. = 5.669 x 10^(-8).. W/m^2.K^4

e = effective emissivity of shield material

T_h, T_c = boundary temps of insulation “

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**"For this problem, we have:"**

h_c = 85 * 10^(-3) "W/m^2. K"

NbyDELTAx = 25 * 100 "layers / m"

sigma = 5.669 * 10^(-8) "W/m^2.K^4 ... Stefan-Boltzmann const."

e = 0.05 ".effective emissivity of shield material"

T_h = 300 "K"

T_c = 20.5 "K"

"Then, we get:"

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| e = 0.05 [-] | $h_c$ = 0.085 [W/m$^{2.K}$] | $k_t$ = 0.000051 [W/m.K] |
| NbyDELTAx = 2500 | $\sigma$ = 5.669E-08 [W/m$^{2.K^4}$] | $T_c$ = 20.5 |
| $T_h$ = 300 [K] | | |

**i.e. Apparent thermal conductivity of this multi-layer insulation is:**

**k_t = 51 μW/m.K…Ans.**

**(b) When the $T_h$, $T_c$ are: 20.5 K and 4.4 K respectively:**

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| e = 0.05 [-] | $h_c$ = 0.085 [W/m$^{2.K}$] | $k_t$ = 0.000034 [W/m.K] |
| NbyDELTAx = 2500 | $\sigma$ = 5.669E-08 [W/m$^{2.K^4}$] | $T_c$ = 4.4 [K] |
| $T_h$ = 20.5 [K] | | |

**i.e. When Th = 20.5 K, Tc = 4.4 K, apparent thermal conductivity of this multi-layer insulation is: k_t = 34 μW/m.K …. Ans.**

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## PROB.V-B.24

**A VAPOR-SHIELDED LIQUID-HELIUM VESSEL HAS CONDUCTANCES OF U2 = 5 mW/K BETWEEN THE OUTER SURFACE AND SHIELD AND U1 = 6 mW/K BETWEEN THE SHIELD AND INNER VESSEL. THE MEAN SPECIFIC HEAT OF THE HELIUM GAS FLOWING THROUGH THE SHIELD IS 5.392 KJ/KG-K, AND THE HEAT OF VAPORIZATION OF THE HELIUM IS 19.69 KJ/KG. THE INNER-VESSEL TEMPERATURE IS 4.4 K (7.9°R), AND THE OUTER-VESSEL TEMPERATURE IS 300 K (540°R). DETERMINE: (A) THE TEMPERATURE OF THE SHIELD, AND (B) THE HEAT-TRANSFER RATE TO THE INNER VESSEL [1].**

**Solution:**

**"Data:"**

T_1 = 4.4 "K ...temp of inner vessel"

T_2 = 300 "K ... temp of outer vessel"

U_1 = 0.006 "W/K ... conductance betweenshield and inner vessel"

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U_2 = 0.005 "W/K ... conductance between outer vessel and shield"

h_fg = 19.69 * 10^3 "J/kg ...heat of vaporization of Helium"

cp = 5392 "J/kg.K ... sp. heat of helium gas flowing through the shield"

**For vapor shielded vessels, Dimensionless temp of the shield is given by:**

$$\theta = \left[\frac{pi_2 + 1}{2 \cdot pi_1 \cdot pi_2}\right] \cdot \left[\left\{1 + \frac{4 \cdot pi_1 \cdot pi_2}{(pi_2 + 1)^2}\right\}^{(1/2)} - 1\right]$$

where:

$$pi_1 = cp \cdot \left[\frac{T_2 - T_1}{h_{fg}}\right]$$

$$pi_2 = \frac{U_1}{U_2}$$

Therefore, we get:

**Unit Settings: SI K kPa kJ mass deg**

| | | | | |
|---|---|---|---|---|
| $cp = 5392$ [J/kg.K] | $h_{fg} = 19690$ [J/kg] | $pi_1 = 80.95$ | $pi_2 = 1.2$ | $\theta = 0.09077$ |
| $T_1 = 4.4$ [K] | $T_2 = 300$ [K] | $U_1 = 0.006$ [W/K] | $U_2 = 0.005$ [W/K] | |

**i.e. We get: $\theta$ = 0.09077**

**Therefore, temp of the shield, $T_s$ is:**

T_s = theta * (T_2 - T_1) + T_1 "K .... temp of shield"

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | | | |
|---|---|---|---|---|
| $cp = 5392$ [J/kg.K] | $h_{fg} = 19690$ [J/kg] | $pi_1 = 80.95$ | $pi_2 = 1.2$ | $\theta = 0.09077$ |
| $T_1 = 4.4$ [K] | $T_2 = 300$ [K] | $T_s = 31.23$ [K] | $U_1 = 0.006$ [W/K] | $U_2 = 0.005$ [W/K] |

**i.e. temp of shield = T_s = 31.23 K ... Ans.**

**Heat transfer rate to the inner vessel, $Q_{s\text{-}1}$:**

Q_s1 = U_1 * (T_s - T_1) "W"

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**We get:**

Unit Settings: SI K kPa kJ mass deg

| | | | | |
|---|---|---|---|---|
| $cp = 5392$ [J/kg.K] | $h_{fg} = 19690$ [J/kg] | $pi_1 = 80.95$ | $pi_2 = 1.2$ | $Q_{s1} = 0.161$ [W] |
| $\theta = 0.09077$ | $T_1 = 4.4$ [K] | $T_2 = 300$ [K] | $T_s = 31.23$ [K] | $U_1 = 0.006$ [W/K] |
| $U_2 = 0.005$ [W/K] | | | | |

**i.e. Heat transfer rate to the inner vessel, $Q_{s-1}$ = 0.161 W … Ans.**

"============================================================"

## PROB.V_B.25

**A VACUUM-JACKETED LIQUID HYDROGEN TRANSFER LINE HAS A 300-MM NOMINAL (12-IN. NOMINAL) INNER LINE AND A 400-MM NOMINAL (16-IN. NOMINAL) OUTER 1INE. BOTH LINES ARE CONSTRUCTED OF 304 STAINLESS STEEL, AND THE WELD EFFICIENCY IS 100 PERCENT. THE OUTER LINE HAS A DISTANCE OF 12.25 M (40.2 FT) BETWEEN SUPPORT POINTS. DETERMINE THE MINIMUM THICKNESS AND SCHEDULE NUMBER FOR THE INNER AND OUTER LINES, FOR A DESIGN INTERNAL PRESSURE OF 600 KPA ABS.[1]**

**Solution:**

From Table 6.9, for the 300 mm nominal inner pipe, the OD is 323.9 mm, and for the 400 mm nominal outer pipe, the OD is 406.4 mm.

From Table 6.1, allowable stress for SS 304 is 129.2 MPa.

Then, minimum thickness of inner pipe is determined from:

"For piping subjected to internal pressure, we have:"

t = p * D_o / (2 * s_a + 0.8 * p) "...thickness of piping"

"where; p = design pressure, D_o = putside dia of pipe, s_a = allowable stress of pipe material"

"For inner pipe, we have:"

L = 12.25 "m"

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p = 600 "kPa"

D_o = 323.9 "mm"

---

s_a = 129.2 * 10^3 "kPa"

Then, thickness of inner pipe is:

**Unit Settings: SI K kPa kJ mass deg**

$D_o$ = 323.9 [mm] L = 12.25 [m] p = 600 [kPa] $s_a$ = 129200 [kPa] t = 0.7507 [mm]

---

"i.e., we get: t = 0.7507 mm"

**"Therefore, from Table 6.9, use 300 mm nominal, schedule 5 pipe, which has a thickness of 4 mm."**

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**Min. thickness of outer pipe:**

**First, assume that it is a 'long' pipe, and calculate the thickness. Then, verify that it is really a long pipe, by checking the criterion for a long pipe.**

**For a long pipe, subjected to buckling from outside atm. pressure:**

---

p_a = 101.3 "kPa"

p_c = 4 * p_a "kPa.... critical pressure for buckling"

nu = 0.28 "Poisson's ratio for SS 304"

E = 207 * 10^6 "kPa.. Young's modulus for SS 304"

D_outer = 406.4 "mm .. OD of outer pipe"

**"Then, thickness is:"**

t_outer = (p_c * (1 - nu^2) / (2 * E ))^(1/3) * D_outer

**Unit Settings: SI K kPa kJ mass deg**

| | | | | |
|---|---|---|---|---|
| $D_o$ = 323.9 [mm] | $D_{outer}$ = 406.4 [mm] | E = 2.070E+08 [-] | L = 12.25 [m] | ν = 0.28 |
| p = 600 [kPa] | $p_a$ = 101.3 | $p_c$ = 405.2 [kPa] | $s_a$ = 129200 [kPa] | t = 0.7507 [mm] |
| $t_{outer}$ = 3.927 [mm] | | | | |

We get: t_outer = 3.927 mm.

Again, from Table 6.9, we see that for 400 nominal pipe, sch 5 has a thickness of 4.2 mm.

**Therefore, choose 400 nominal, schedule 5 pipe for outer pipe.**

---

"And:"

**t_outersch5 = 4.2 "mm...outer cylinder thickness for sch 5 pipe"**

**"Now, verify the criterion for a 'long' pipe is satisfied:**

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**We call the EES Procedure written for this purpose, earlier:"**

CALL Test_for_long_cylinder(L, D_outer*10^(-3), t_outersch5*10^(-3), nu : LbyD_o, RHS, RESULT$)

We get:

**Unit Settings: SI K kPa kJ mass deg**

$D_o$ = 323.9 [mm]

E = 2.070E+08 [-]

$LbyD_o$ = 30.14

p = 600 [kPa]

$p_c$ = 405.2 [kPa]

RHS = 10.99

t = 0.7507 [mm]

$t_{outersch5}$ = 4.2 [mm]

$D_{outer}$ = 406.4 [mm]

L = 12.25 [m]

ν = 0.28

$p_a$ = 101.3

RESULT$ = ' It is a long cylinder !'

$s_a$ = 129200 [kPa]

$t_{outer}$ = 3.927 [mm]

**"Therefore, it is confirmed that it is a long cylinder."**

"============================================================"

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## PROB.V-B.26

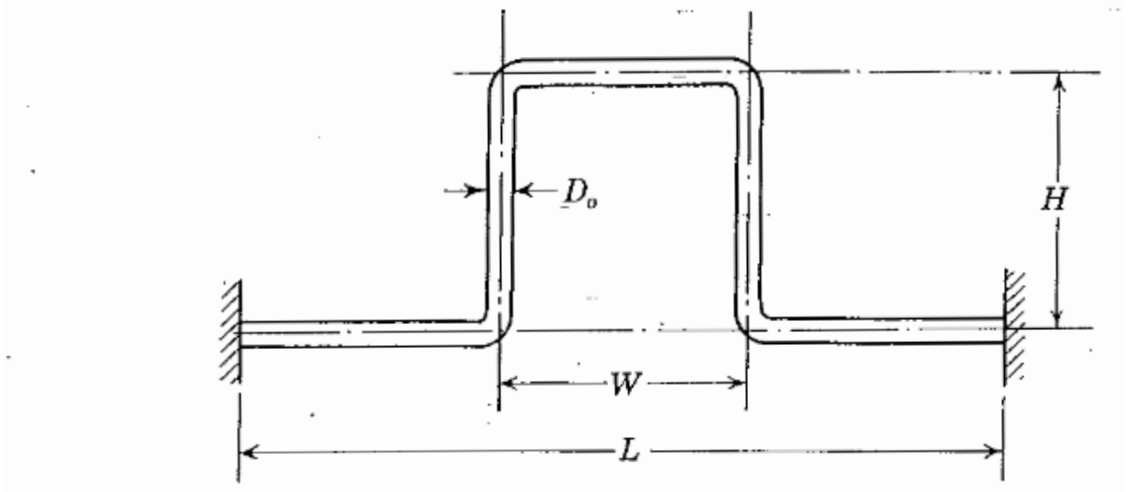
**DETERMINE THE MAXIMUM THERMAL STRESS INDUCED IN A U-BEND SECTION, IF THE LINE IS INITIALLY AT 300 K (540°R) IN THE STRESS-FREE CONDITION, AND IS COOLED TO 80 K (L44°R). THE LINE IS A 150-MM NOMINAL (6-IN. NOMINAL) SCHEDULE 5 STAINLESS STEEL PIPE, WITH A LENGTH OF 12 M (39.4 FT) BETWEEN FIXED POINTS. THE U-BEND HAS DIMENSIONS OF W = 6 M (19.7 FT) AND H = 3 M (9.8 FT). COMPARE THIS VALUE OF STRESS WITH THE THERMAL STRESS THAT WOULD BE INDUCED IF A 12 M LENGTH OF STRAIGHT PIPE OF THE SAME DIAMETER WITH BOTH ENDS RIGIDLY FIXED WERE COOLED THROUGH THE SAME TEMPERATURE RANGE.[1]**

**Solution:**

---

Recollect from Part-V-A that:

**Fig. 6.13. U-bend :**




Maximum stress induced by thermal contraction in a U-bend is given by:

For $\alpha = W/L >= 1/2$:

$$\frac{\sigma_{max} \cdot L}{E \cdot e_t \cdot D_o} = \frac{\alpha + \beta}{B} \cdot \left[ 1 + \frac{(1 + 2 \cdot \beta) \cdot D_o}{4 \cdot (\alpha + \beta) \cdot H} \right]$$

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**For $\alpha = W/L < 1/2$:**

$$\frac{\sigma_{max} \cdot L}{E \cdot e_t \cdot D_o} = \frac{1 - \alpha + \beta}{B} \cdot \left[ 1 + \frac{(1 + 2 \cdot \beta) \cdot D_o}{4 \cdot (1 - \alpha + \beta) \cdot H} \right]$$

where:

$$B = \frac{2}{3} \cdot \beta \cdot \left[ \beta \cdot (2 + \beta) + 3 \cdot \alpha \cdot (1 - \alpha) + \frac{3}{8} \cdot (1 + 2 \cdot \beta) \cdot \left( \frac{D_0}{H} \right)^2 \right]$$

$$\alpha = \frac{W}{L} \qquad \beta = \frac{H}{L}$$

$$e_t = \int_{T_c}^{T_h} \lambda_t dT \quad = \text{unit thermal strain, see Table 6.16}$$

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$D_o$ = outside dia of line

E = Young's Modulus

---

"We have:"

W = 6 "m ... width of U bend"

H = 3 "m ... height of bend"

L = 12 "m ... distance between fixed points"

D_o = 168.3 * 10^(-3) "m...OD of 150 mm nominal pipe"

nu = 0.28 "Poisson's ratio for SS 304"

E = 207 * 10^6 "kPa " Young'd modulus for SS 304"

"e_t = thermal strain = DELTAL / L ... use the EES Function written earlier for SS 304 to find DELTALbyL:"

TL = 80 "K"

TH = 300 "K"

CALL DeltaLbyL_SS304(TL, TH : DLbyL_atTL, DLbyL_atTH, DLbyL_at_TL_TH)

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| $DLbyL_{atTH}$ = 0.00307 | $DLbyL_{atTL}$ = 0.00017 | $DLbyL_{at,TL,TH}$ = 0.0029 | $D_o$ = 0.1683 [m] |
| E = 2.070E+08 [kPa] | $e_t$ = 0.0029 | H = 3 [m] | L = 12 [m] |
| $\nu$ = 0.28 | TH = 300 [K] | TL = 80 [K] | W = 6 [m] |

**"Therefore, we get: DLbyL_at_TL_TH = 0.0029"**

e_t = DLbyL_at_TL_TH "Unit strain "

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**"Now, calculate dimensionless parameters alpha and beta:"**

alpha = W / L

beta = H / L

"We get: alpha = 0.5, and beta = 0.25"

"Now, for alpha > = 0.5, we have:"

(sigma_max * L) / (E * e_t * D_o) = ((alpha + beta) / B ) * ( 1 + ( 1 + 2 * beta) * D_o / ( 4 * (alpha + beta) * H))

B = (2 / 3) * beta * (beta * (2 + beta) +3 * alpha * (1 - alpha) + (3 / 8) * ( 1 + 2 * beta) * ( D_o / H)^2)

**We get:**

Unit Settings: SI K kPa kJ mass deg

| | | | |
|---|---|---|---|
| $\alpha$ = 0.5 | B = 0.219 | $\beta$ = 0.25 | $DLbyL_{atTH}$ = 0.00307 |
| $DLbyL_{atTL}$ = 0.00017 | $DLbyL_{at,TL,TH}$ = 0.0029 | $D_o$ = 0.1683 [m] | E = 2.070E+08 [kPa] |
| $e_t$ = 0.0029 | H = 3 [m] | L = 12 [m] | $\nu$ = 0.28 |
| $\sigma_{max}$ = 29636 [kPa] | TH = 300 [K] | TL = 80 [K] | W = 6 [m] |

**Thus, max thermal stress induced = $\sigma_{max}$ = 29636 kPa = 29.636 MPa ... Ans.**

**(b) If a 12 m length of straight pipe were used, without any U-bend, with the ends rigidly fixed, what would be the thermal stress?**

"Between 300 K and 80 K, thermal contraction is:"

DELTAL = e_t * L "m"

"And, thermal stress = Young's modulus * strain"

"So, we get:"

sigma_max_noUbend = E * e_t

We get:

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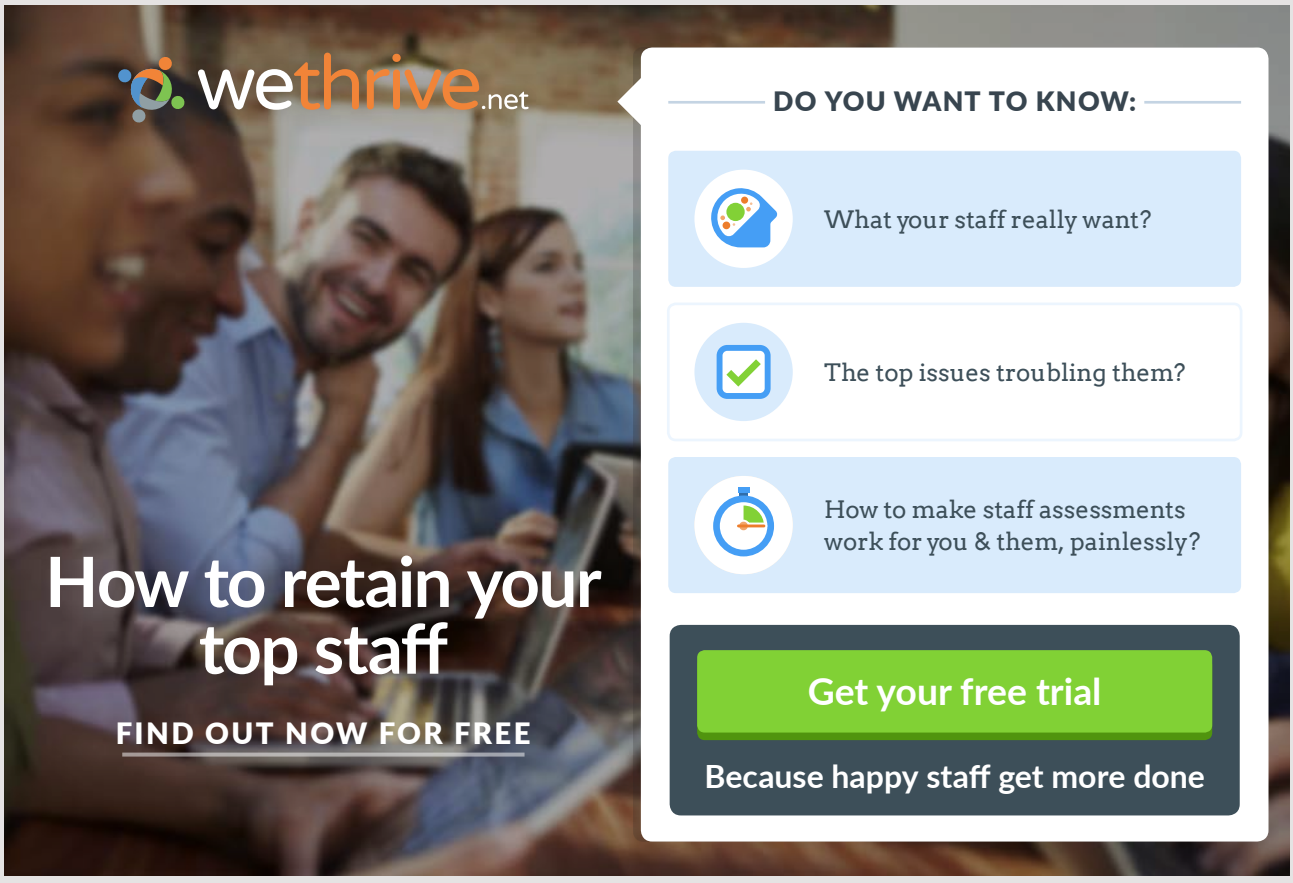
**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $\alpha$ = 0.5 | B = 0.21905 | $\beta$ = 0.25 |
| $\Delta L$ = 0.0348 [m] | $DLbyL_{atTH}$ = 0.00307 | $DLbyL_{atTL}$ = 0.00017 |
| $DLbyL_{at,TL,TH}$ = 0.0029 | $D_o$ = 0.1683 [m] | E = 2.070E+08 [kPa] |
| $e_t$ = 0.0029 | H = 3 [m] | L = 12 [m] |
| $\nu$ = 0.28 | $\sigma_{max}$ = 29636 [kPa] | $\sigma_{max,noUbend}$ = 600300 [kPa] |
| TH = 300 [K] | TL = 80 [K] | W = 6 [m] |

**i.e. thermal stress when there is no U-bend = 600300 kPa = 600.3 MPa....Ans.**

---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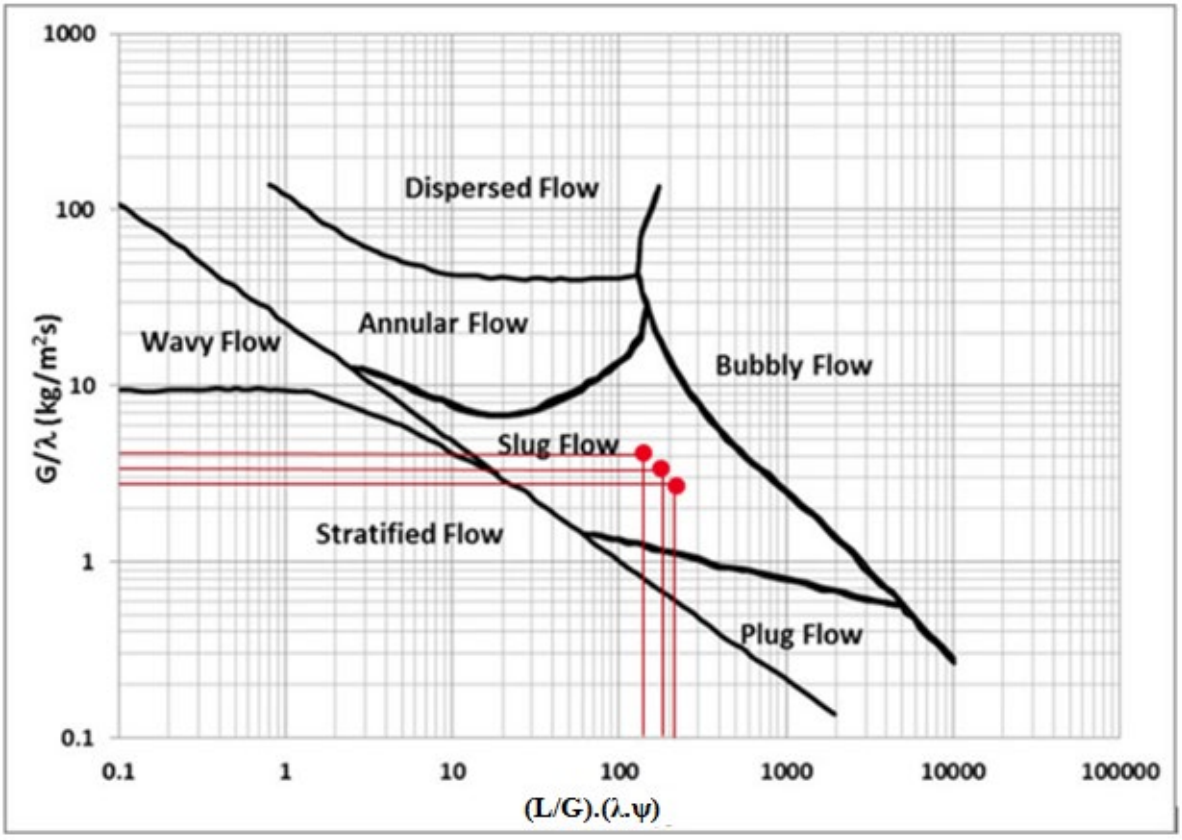
## PROB.V-B.27

**LIQUID NITROGEN FLOWS IN A 200-MM NOMINAL (8-IN. NOMINAL) SCHEDULE 5 PIPE AT A TOTAL FLOW RATE OF 4.50 KG/S (35 700 LBM/HR) AND A FLUID QUALITY OF 0.150. THE LIQUID TEMPERATURE IS 85 K (153°R), AND THE LIQUID AND VAPOR DENSITIES ARE 771 KG/M3 AND 9.376 KG/M3, RESPECTIVELY. THE LIQUID VISCOSITY AND SURFACE TENSION ARE 0.119 mPa-s AND 7.18 mN/m. DETERMINE THE TWO-PHASE FLOW REGIME.[1]**

**Solution:**

With reference to the Baker diagram shown below, we have to find X and Y coordinates and, then, find out the flow regime. (See Part V_A for more details)




**We have:**

X - axis: $\lambda^* (G_L/G_G) * \psi$ Y--axis: $G_G/\lambda$

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**Data:**

D = 213.56 * 10^(-3) "m... ID of 200 mm nominal pipe, with OD = 219.1 mm, thickness = 2.77 mm"

A = pi * D^2 / 4 "m^2 .... area of cross-section"

rho_a = 1.2 "kg/m^3 .... density of air"

rho_w = 998 "kg/m^3 ... density of water"

---

rho_L = 771 "kg/m^3 ... density of liquid"

rho_G = 9.376 "kg/m^3 ... density of vapor"

mu_L = 0.119 * 10^(-3) "Pa.s .... viscosity of liquid"

mu_w = 0.001 "Pa.s .... viscosity of water"

sigma_L = 7.18 * 10^(-3) "N/m .... surface tension"

sigma_w = 0.073 "N/m ... surface tension of water"

x = 0.15 "...quality"

m_tot = 4.5 "kg/s ... total flow rate"

"Therefore:"

m_G = m_tot * x "kg/s ... flow rate of vapor"

m_L = m_tot - m_G "kg/s ... flow rate of liquid"

G_L = m_L / A "kg/s.m^2 "

G_G = m_G / A "kg/s.m^2 "

"Now:"

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lambda = (rho_G * rho_L / (rho_a * rho_w))^(1/2)

psi = (sigma_w / sigma_L) * ((mu_L / mu_w) * (rho_w / rho_L)^2)^(1/3)

"Then:"

"X - axis of Baker diagram is:"

X_axis = (G_L / G_G) * (lambda * psi)

"And:"

"Y - axis of Baker diagram is:"

Y_axis = (G_G / lambda)

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**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| $A = 0.03582$ [$m^2$] | $D = 0.2136$ [m] | $G_G = 18.84$ [$kg/s.m^2$] | $G_L = 106.8$ [$kg/s.m^2$] |
| $\lambda = 2.457$ [-] | $\mu_L = 0.000119$ [Pa-s] | $\mu_w = 0.001$ [Pa-s] | $m_G = 0.675$ [kg/s] |
| $m_L = 3.825$ [kg/s] | $m_{tot} = 4.5$ [kg/s] | $\psi = 5.94$ [-] | $\rho_a = 1.2$ [$kg/m^3$] |
| $\rho_G = 9.376$ [$kg/m^3$] | $\rho_L = 771$ [$kg/m^3$] | $\rho_w = 998$ [$kg/m^3$] | $\sigma_L = 0.00718$ [N/m] |
| $\sigma_w = 0.073$ [N/m] | $x = 0.15$ | $X_{axis} = 82.69$ | $Y_{axis} = 7.67$ [$kg/s.m^2$] |

**Then, from the Baker diagram, we see that: for X = 82.69 and Y = 7.67, the flow regime is: *SLUG FLOW*.**

---

## PROB.V-B.28

### WRITE AN EES PROCEDURE TO DETERMINE THE PRESSURE DROP IN TWO-PHASE FLOW.

**We use equations given in Barron [1] for Lockhart-Martinelli correlation.**

```
PROCEDURE Lockhart_Martinelli_PrDrop2(D, rho_L, rho_G, mu_L, mu_G, m_L, m_G :
G_L, G_G, Re_L, Re_G, f_L, f_G, dPdL_L, X_tt, C, phi_L, C_L, C_G, dPdL_TP)

{Determines the pressure drop in two-phase flow with Lockhart-Martinelli correlation, with
equations as given in Ref.[1].}

"Inputs:

Subscript L for Liquid, subscript G for Vapor

D = ID of pipe, m; rho = density, kg/m^3; mu = viscosity, Pa-s; m = mass flow rate, kg/s

Outputs:

G_L = mass flow rate of liquid per unit area, kg/s.m^2

G_G = mass flow rate of vapor per unit area, kg/s.m^2

Re_L = Reynolds Number of Liquid

Re_G = Reynolds Number of vapor
```

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F_L = friction factor for only the liquid flowing full in pipe

F_G = friction factor for only the vapor flowing full in pipe

dPdL_L = Pressure drop per unit length (Pa/m) if only the liquid is flowing

X_tt = Lokhart-Martinelli parameter

C = Constant in the expression for the multiplier (fL) to dPdLL to calculate two-phase pressure drop

Φ_L = the multiplier to dPdLL to calculate two-phase pressure drop

C_L = constant to calculate Xtt

C_G = constant to calculate Xtt

dPdL_TP = Two-phase pressure drop per unit length, Pa/m "

A = pi* D^2 / 4 "m^2 .... area of cross-section"

G_L = m_L / A "kg/s.m^2 .... for liquid"

G_G = m_G / A "kg/s.m^2 ... for vapor"

Re_L = G_L * D / mu_L "..Reynold's number for liquid flow alone in pipe"

Re_G = G_G *D / mu_G "..Reynold's number for vapor flow alone in pipe"

```
IF (Re_G < 2000) THEN
    m_vap = 1
    C_G = 64
ENDIF
IF (Re_L < 2000) THEN
    n_liq = 1
```

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C_L = 64

ENDIF

IF ( Re_G < 50000) AND (RE_G > 3000) THEN m_vap = 0.25

IF (Re_G >= 50000) THEN m_vap = 0.2

IF ( Re_L < 50000) AND (RE_L > 3000) THEN n_liq = 0.25

IF (Re_L >= 50000) THEN n_liq = 0.2

IF ( Re_G < 50000) AND (RE_G > 3000) THEN C_G = 0.316

IF (Re_G >= 50000) THEN C_G = 0.184

IF ( Re_L < 50000) AND (RE_L > 3000) THEN C_L = 0.316

IF (Re_L >= 50000) THEN C_L = 0.184

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```
x = m_G / (m_L + m_G)

X_tt = ((C_L * Re_G^m_vap * rho_G) * ((1 - x) / x)^2 / (C_G * Re_L ^n_liq * rho_L))^(1/2)

IF ( Re_L < 3000) AND (RE_G < 3000) THEN C = 5

IF ( Re_L > 3000) AND (RE_G < 3000) THEN C = 10

IF ( Re_L < 3000) AND (RE_G > 3000) THEN C = 12

IF ( Re_L > 3000) AND (RE_G > 3000) THEN C = 20

phi_L = (X_tt^2 + C * X_tt + 1)^(1/2) / X_tt

IF ( Re_L < 50000) AND (RE_L > 3000) THEN f_L = 0.316 * Re_L^(-0.25)

IF (Re_L >= 50000) THEN f_L = 0.184 * Re_L^(-0.2)

IF ( Re_G < 50000) AND (RE_G > 3000) THEN f_G = 0.316 * Re_G^(-0.25)

IF (Re_G >= 50000) THEN f_G = 0.184 * Re_G^(-0.2)

dPdL_L = (f_L / 2) * G_L^2 / (rho_L * D)

dPdL_TP = phi_L^2 * dPdL_L

END

"============================================================"
```

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## PROB.V-B.29

**DETERMINE THE FRICTIONAL PRESSURE DROP FOR ADIABATIC FLOW OF TWO-PHASE HYDROGEN IN A 150-MM NOMINAL (6-IN. NOMINAL) SCHEDULE 5 PIPE FOR A TOTAL MASS FLOW RATE OF 4.00 KG/S (31,750 LBM/HR) AND A FLUID QUALITY OF 0.10. THE LIQUID HYDROGEN IS FLOWING AT AN AVERAGE PRESSURE OF 354.6 KPA (3.50 ATM). THE LENGTH OF THE LINE IS 160 M (525 FT).[1]**

**Solution:**

For hydrogen at 354.6 kPa (saturation temperature = 25.478 K, we find the following fluid properties, from NIST website:

Ref: https://webbook.nist.gov/chemistry/fluid/

# Liquid Phase Data

## Data on Saturation Curve

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) |
|---|---|---|---|---|---|---|---|
| 25.478 | 0.35460 | 63.944 | 0.015639 | 55.261 | 60.807 | 2.4843 | 5.9820 |

| Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Surf. Tension (N/m) | Phase |
|---|---|---|---|---|---|---|
| 13.835 | 944.96 | -0.31667 | 9.1415 | 0.10373 | 0.0011292 | liquid |

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# Vapor Phase Data

## Data on Saturation Curve

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) |
|---|---|---|---|---|---|---|---|
| 25.478 | 0.35460 | 4.2933 | 0.23292 | 380.82 | 463.41 | 18.286 | 6.8055 |

| Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Phase |
|---|---|---|---|---|---|
| 15.873 | 376.29 | 13.951 | 1.4188 | 0.023549 | vapor |

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**Data:**

D = 0.1627 "m.. ID of 150 mm nominal pipe"

rho_L = 63.944 " liq.density, kg/m^3"

mu_L =9.1415 * 10^(-6) " liq viscosity, Pa-s"

m_L = 3.6 " liq mass flow rate, kg/s "

rho_G = 4.2933 " vap.density, kg/m^3"

mu_G = 1.4188 * 10^(-6) " vap viscosity, Pa-s"

m_G = 0.4 "vap mass flow rate, kg/s "

**Let us use the EES Procedure written above:**

CALL Lockhart_Martinelli_PrDrop2(D, rho_L, rho_G, mu_L, mu_G, m_L, m_G : G_L, G_G, Re_L, Re_G, f_L, f_G, dPdL_L, X_tt, C, phi_L, C_L, C_G, dPdL_TP)

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| C = 20 | $C_G$ = 0.184 | $C_L$ = 0.184 | D = 0.1627 [m] |
| **$dPdL_L$ = 13.36** [Pa/m] | $dPdL_{TP}$ = 134.4 [Pa/m] | $f_G$ = 0.00991 | $f_L$ = 0.009269 |
| $G_G$ = 19.24 [kg/s.m$^2$] | $G_L$ = 173.2 [kg/s.m$^2$] | $\mu_G$ = 0.000001419 [Pa-s] | $\mu_L$ = 0.000009142 [Pa-s] |
| $m_G$ = 0.4 [kg/s] | $m_L$ = 3.6 [kg/s] | $\phi_L$ = **3.172** | $Re_G$ = 2.206E+06 |
| $Re_L$ = 3.082E+06 | $\rho_G$ = 4.293 [kg/m$^3$] | $\rho_L$ = 63.94 [kg/m$^3$] | $X_{tt}$ = 2.255 |

**We note that two-phase pressure drop is: $dPdL_{TP}$ = 134.4 Pa/m**

Now, length of pipe is, by data, L = 160 m

**Then, total two-phase pressure drop = 134.4 x 160 = 2.1504E04 Pa = 21.5 kPa … Ans.**

**(b) Now, determine the flow regime from the Baker diagram:**

We have, additional data:"

rho_a = 1.2 "kg/m^3 .... density of air"

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rho_w = 998 "kg/m^3 ... density of water"

mu_w = 0.001 "Pa.s .... viscosity of water"

sigma_L = 0.0011292 "N/m .... surface tension"

sigma_w = 0.073 "N/m ... surface tension of water"

"Now:"

lambda = (rho_G * rho_L / (rho_a * rho_w))^(1/2)

psi = (sigma_w / sigma_L) * ((mu_L / mu_w) * (rho_w / rho_L)^2)^(1/3)

"Then:"

---

**"X_axis of Baker diagram is:"**

X_axis = (G_L / G_G) * (lambda * psi)

"And:"

**"Y - axis of Baker diagram is:"**

Y_axis = (G_G / lambda)

"We get:"

"X - axis = 363.8, and Y-axis = 40.18 kg/s.m^2"

**Then, from the Baker diagram, we see that: for X = 363.8 and Y = 40.18, the flow regime is: BUBBLE FLOW ... Ans.**

"============================================================"

**Note that we can use the built-in functions of EES to get fluid properties instead of going to NIST website; in fact, it is more convenient.**

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**Above problem is solved again below, with fluid properties obtained from EES:**

"Prob.V-B.29 Determine the frictional pressure drop for adiabatic flow of two-phase hydrogen in a 150-mm nominal (6-in. nominal) schedule 5 pipe for a total mass flow
rate of 4.00 kg/s (31,750 lbm/hr) and a fluid quality of 0.10. The liquid hydrogen is flowing at an average pressure of 354.6 kPa (3.50 atm). The length of the line is 160 m (525 ft).[1]"

"Solution:"

"For hydrogen at 354.6 kPa (saturation temperature = 25.478 K ), we find the fluid properties from EES: "

"Data:"

```
D = 0.1627 "m.. ID of 150 mm nominal pipe"

m_L = 3.6 " liq mass flow rate, kg/s "

m_G = 0.4 "vap mass flow rate, kg/s "

P_fluid = 354.6 "kPa"

"Get properties of sat. fluid from the built-in functions in EES:"

 rho_L = Density(Hydrogen,P=P_fluid,x=0)  " liq.density, kg/m^3"

 mu_L = Viscosity(Hydrogen,P=P_fluid,x=0) " liq viscosity, Pa-s"

rho_G = Density(Hydrogen,P=P_fluid,x=1)  " vap.density, kg/m^3"

 mu_G = Viscosity(Hydrogen,P=P_fluid,x=1) " vap viscosity, Pa-s"
```

"Now, let us use the EES Procedure written above:"

```
CALL   Lockhart_Martinelli_PrDrop2(D, rho_L, rho_G, mu_L, mu_G, m_L, m_G : G_L, G_G, Re_L,
Re_G, f_L, f_G, dPdL_L, X_tt, C, phi_L, C_L, C_G, dPdL_TP)
```

"We get:"

**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| $C$ = 20 | $C_G$ = 0.184 | $C_L$ = 0.184 | $D$ = 0.1627 [m] |
| $dPdL_L$ = **13.25** [Pa/m] | $dPdL_{TP}$ = **136.2** [Pa/m] | $f_G$ = 0.01028 | $f_L$ = 0.009194 |
| $G_G$ = 19.24 [kg/s.m$^2$] | $G_L$ = 173.2 [kg/s.m$^2$] | $\mu_G$ = **0.000001707** [Pa-s] | $\mu_L$ = **0.000008776** [Pa-s] |
| $m_G$ = 0.4 [kg/s] | $m_L$ = 3.6 [kg/s] | $\phi_L$ = 3.206 | $P_{fluid}$ = 354.6 [kPa] |
| $Re_G$ = 1.833E+06 | $Re_L$ = 3.210E+06 | $\rho_G$ = **4.293** [kg/m$^3$] | $\rho_L$ = **63.94** [kg/m$^3$] |
| $X_{tt}$ = **2.205** | | | |

**Note that now dPdLTP = 136.2 Pa/m, whereas earlier it was 134.4 Pa/m (Not much different).**

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## PROB.V-B.30

### WRITE AN EES PROCEDURE FOR TWO-PHASE FLOW PRESSURE DROP IN A PIPE; INCLUDE THE EFFECT OF ROUGHNESS TOO.

**Solution:**

**We will use the Haaland equation (given below) for friction factor, which includes the effect of pipe roughness.**

$$\frac{1}{\sqrt{f}} = -1.8 \log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{\mathrm{Re}}\right]$$

Haaland equation is an approximation of the implicit Colebrook-White eqn. (Ref: Wikipedia: https://en.wikipedia.org/wiki/Darcy_friction_factor_formulae#Haaland_equation

This is valid for only turbulent flow i.e. for $\mathrm{Re}_D > 4000$.

**Note: For typical roughness values for pipes, and for Moody's diagram, see Part V-A.**

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**We write the EES Procedure below:**

---

PROCEDURE Lockhart_Martinelli_PrDrop(epsilon, D, rho_L, rho_G, mu_L, mu_G, m_L, m_G : G_L, G_G, Re_L, Re_G, f_L, f_G, dPdL_L, dPdL_G, X_tt, phi_L, phi_G, dPdL_tot1, dPdL_tot2)

{Determines the pressure drop in two-phase flow with Lockhart-Martinelli correlation, with Haaland equation for friction factor, and taking into account the roughness of pipe too.}

"Inputs:

epsilon = roughness of pipe, m; D = ID of pipe, m; ρ_L = density of liquid, kg/m3;

rho_G = density of vapor, kg/m3; mu_L = viscosity of liquid, Pa-s; mu_G = viscosity of vapor, Pa-s;

m_L = mass flow rate of liquid, kg/s; m_G = mass flow rate of vapor, kg/s

Outputs:

A = area of cross-section of pipe, m^2; G_L = mass flow rate of liq. / unit area, kg/s.m2;

G_G = mass flow rate of vap. / unit area, kg/s.m2; Re_L = Reynold's number for liquid flow;

Re_G = Reynold's number for vapor flow;

f_L = friction factor for liquid flow; f_G = friction factor for vapor flow;

dPdL_L = pressure drop for liquid, per unit length, Pa/m;

dPdL_G = pressure drop for vapor, per unit length, Pa/m;

X_tt = Lockhart-Martinelli parameter

phi_L = multiplication factor for liquid flow to get pressure drop in two-phase flow;

phi_G = multiplication factor for vapor flow to get pressure drop in two-phase flow;

dPdL_tot1 = Two-phase pressure drop based on liquid flow, Pa/m

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```
dPdL_tot2 = Two-phase pressure drop based on vapor flow, Pa/m "

A = pi* D^2 / 4 "m^2 .... area of cross-section"

G_L = m_L / A "kg/s.m^2 .... for liquid"

G_G = m_G / A "kg/s.m^2 ... for vapor"

Re_L = G_L * D / mu_L "..Reynold's number for liquid flow alone in pipe"

Re_G = G_G *D / mu_G "..Reynold's number for vapor flow alone in pipe"

IF (Re_L < 4000) Or (Re_G < 4000) THEN

    CALL ERROR ('Re_L and Re_G both should be > 4000 !!')

ENDIF

IF (Re_L >= 4000) THEN f_L = ( 1/ (-1.8 * log10((epsilon / (D * 3.7))^1.11 + 6.9 /
Re_L)))^2

IF (Re_G >= 4000) THEN f_G = ( 1/ (-1.8 * log10((epsilon / (D * 3.7))^1.11 + 6.9 /
Re_G)))^2

dPdL_L = (f_L * G_L^2) / (2 * rho_L * D)

dPdL_G = (f_G * G_G^2) / (2 * rho_G * D)

X_tt = (dPdL_L / dPdL_G )^(1/2)

phi_G = (1 + 18 * X_tt + X_tt^2)^(1/2)

dPdL_tot1 = phi_G^2 * dPdL_G

phi_L = (1 + 18 / X_tt +1 / X_tt^2)^(1/2)

dPdL_tot2 = phi_L^2 * dPdL_L

END

"============================================================"
```

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**Solve Prob.V_B.29 using the above EES Procedure:**

## PROB.V-B.31

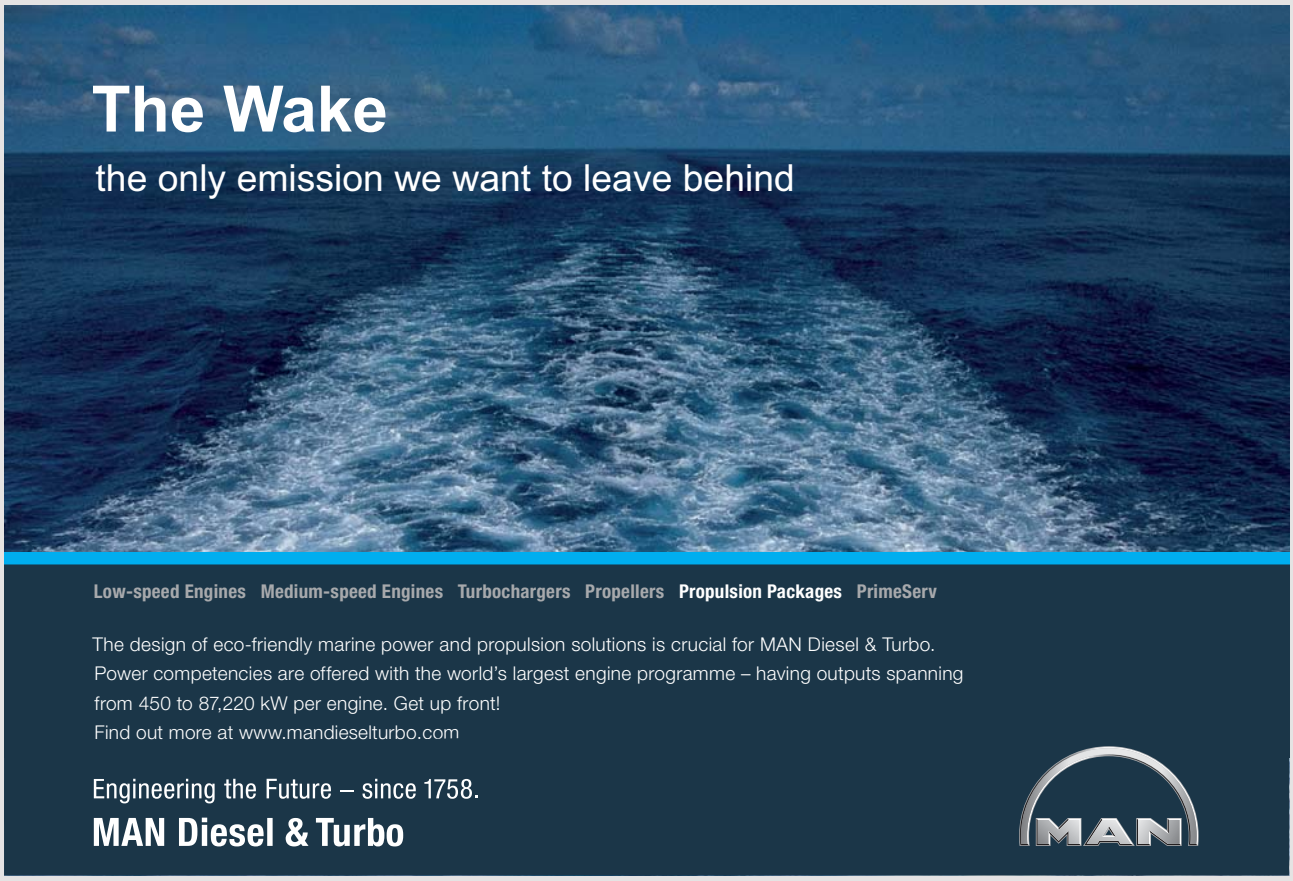
**DETERMINE THE FRICTIONAL PRESSURE DROP FOR ADIABATIC FLOW OF TWO-PHASE HYDROGEN IN A 150-MM NOMINAL (6-IN. NOMINAL) SCHEDULE 5 PIPE FOR A TOTAL MASS FLOW RATE OF 4.00 KG/S (31,750 LBM/HR) AND A FLUID QUALITY OF 0.10. THE LIQUID HYDROGEN IS FLOWING AT AN AVERAGE PRESSURE OF 354.6 KPA (3.50 ATM). THE LENGTH OF THE LINE IS 160 M (525 FT).[1]**

**"We have:"**

```
D = 0.1627 "m.. ID of pipe for 150 mm nominal pipe"

rho_L = 63.944 " liq.density, kg/m^3"

mu_L =9.1415 * 10^(-6) " liq viscosity, Pa-s"
```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m_L = 3.6 " liq mass flow rate, kg/s "

rho_G = 4.2933 " vap.density, kg/m^3"

mu_G = 1.4188 * 10^(-6) " vap viscosity, Pa-s"

m_G = 0.4 "vap mass flow rate, kg/s "

epsilon = 0

CALL Lockhart_Martinelli_PrDrop(epsilon, D, rho_L, rho_G, mu_L, mu_G, m_L, m_G : G_L, G_G, Re_L, Re_G, f_L, f_G, dPdL_L, dPdL_G, X_tt, phi_L, phi_G, dPdL_tot1, dPdL_tot2)

"We get:"

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $D$ = 0.1627 [m] | $dPdL_G$ = 2.699 | **$dPdL_L$ = 13.93** [Pa/m] |
| $dPdL_{tot1}$ = 127.0030 [Pa/m] | **$dPdL_{tot2}$ = 127.0030** [Pa/m] | $\varepsilon$ = 0 |
| $f_G$ = 0.01019 | $f_L$ = 0.009669 | $G_G$ = 19.24 [kg/s.m$^2$] |
| $G_L$ = 173.2 [kg/s.m$^2$] | $\mu_G$ = 0.000001419 [Pa-s] | $\mu_L$ = 0.000009142 [Pa-s] |
| $m_G$ = 0.4 [kg/s] | $m_L$ = 3.6 [kg/s] | $\phi_G$ = 6.86 |
| $\phi_L$ = **3.019** | $Re_G$ = 2.206E+06 | $Re_L$ = 3.082E+06 |
| $\rho_G$ = 4.293 [kg/m$^3$] | $\rho_L$ = 63.94 [kg/m$^3$] | $X_{tt}$ = **2.272** |

**i.e. dPdL_twophase = 127 Pa/m .. Ans....**

**The value obtained with this simple EES Procedure nearly the same as that obtained earlier, with a more complicated Procedure.**

"============================================================"

**(b) If the roughness of pipe is 0.001 m, what will be new pressure drop?**

**Put epsilon = 0.001 and apply the above EES Procedure:**

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**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| D = 0.1627 [m] | $dPdL_G$ = 8.6 | **$dPdL_L$ = 46.76** [Pa/m] |
| $dPdL_{tot1}$ = 416.2989 [Pa/m] | **$dPdL_{tot2}$ = 416.2989** [Pa/m] | **ε = 0.001** [m] |
| $f_G$ = 0.03246 | $f_L$ = 0.03245 | $G_G$ = 19.24 [kg/s.m$^2$] |
| $G_L$ = 173.2 [kg/s.m$^2$] | $\mu_G$ = 0.000001419 [Pa-s] | $\mu_L$ = 0.000009142 [Pa-s] |
| $m_G$ = 0.4 [kg/s] | $m_L$ = 3.6 [kg/s] | $\phi_G$ = 6.958 |
| $\phi_L$ = **2.984** | $Re_G$ = 2.206E+06 | $Re_L$ = 3.082E+06 |
| $\rho_G$ = 4.293 [kg/m$^3$] | $\rho_L$ = 63.94 [kg/m$^3$] | $X_{tt}$ = **2.332** |

**i.e. Two-phase pressure drop, with pipe roughness of epsilon = 0.001 m is:**
**= 416.299 Pa/m … Ans.**

"============================================================"

## PROB.V-B.32

**DETERMINE THE FRICTIONAL PRESSURE DROP FOR ADIABATIC FLOW OF LIQUID NITROGEN IN A 200-MM NOMINAL (8-IN. NOMINAL) SCHEDULE 5 PIPE FOR A TOTAL FLOW RATE OF 4.50 KG/S (35 700 LBM/HR) AND A FLUID QUALITY OF 0.150. THE LIQUID TEMPERATURE IS 85 K (153°R), AND THE LENGTH OF PIPE LINE IS 300 M (984 FT).[1]**

**Solution:**

**Properties of Nitrogen at sat. temp of 85 K:**
**Ref:** https://webbook.nist.gov/chemistry/fluid/

# Liquid Phase Data

## Data on Saturation Curve

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) |
|---|---|---|---|---|---|---|---|
| 85.000 | 0.22886 | 770.13 | 0.0012985 | -106.46 | -106.16 | 3.0277 | 1.0429 |

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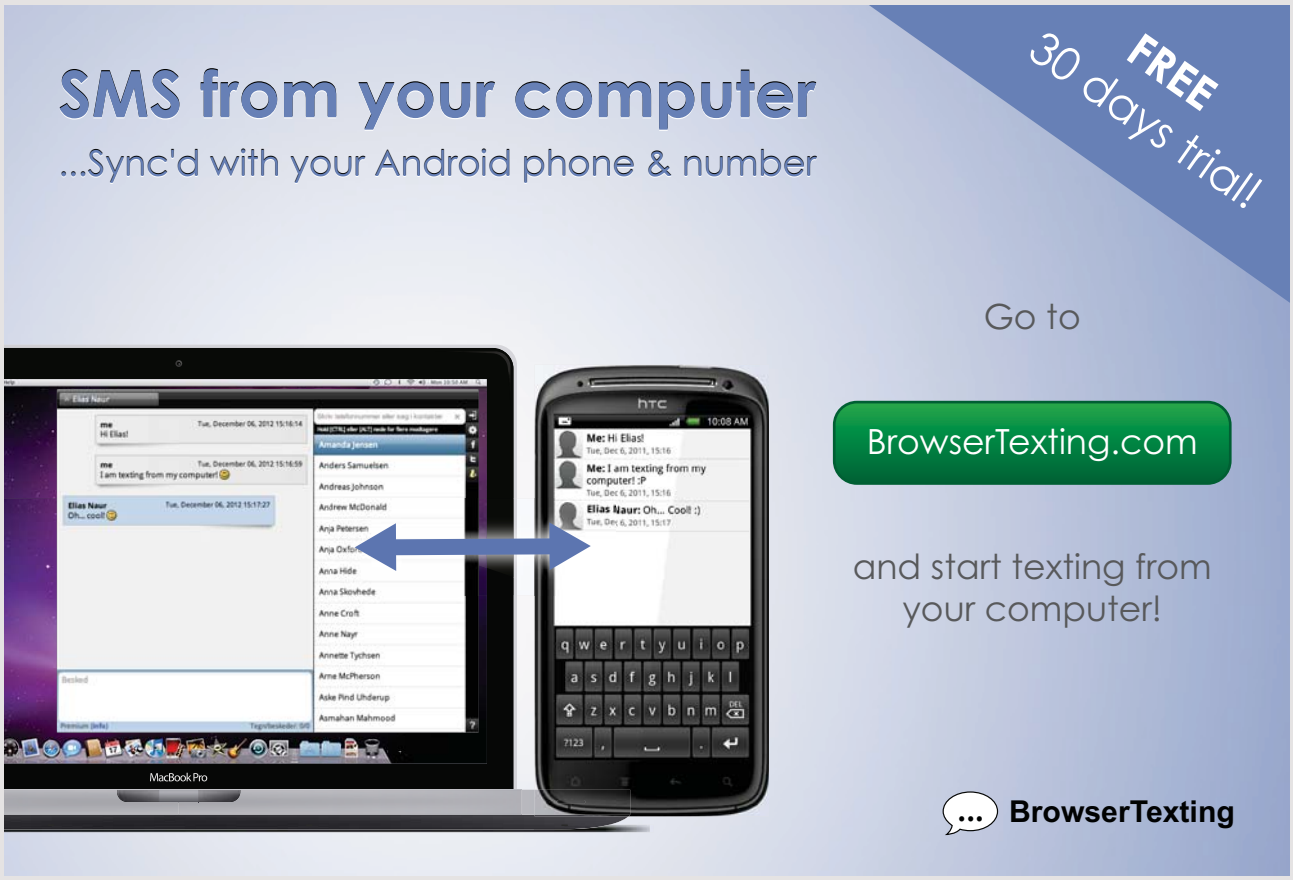
| Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Surf. Tension (N/m) | Phase |
|---|---|---|---|---|---|---|
| 2.0906 | 772.44 | -0.28135 | 121.11 | 0.12993 | 0.0071627 | liquid |

# Vapor Phase Data

## Data on Saturation Curve

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) |
|---|---|---|---|---|---|---|---|
| 85.000 | 0.22886 | 9.8241 | 0.10179 | 59.056 | 82.352 | 5.2454 | 0.79094 |

| Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Phase |
|---|---|---|---|---|---|
| 1.1957 | 179.68 | 22.923 | 6.0405 | 0.0083518 | vapor |

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**Now, let us write all data:**

D = 213.56E-03 "m.. ID of pipe for 200 mm nominal pipe, with OD = 219.1 mm, thickness = 2.77 mm"

A = pi * D^2 /4 "m^2 ... area of cross-section of pipe"

rho_L = 770.13 " liq.density, kg/m^3"

mu_L =121.11 * 10^(-6) " liq viscosity, Pa-s"

m_tot = 4.5 "kg/s ... total flow rate"

x = 0.15 "..quality of flowing fluid"

m_G = m_tot * x "vap mass flow rate, kg/s "

m_L = m_tot - m_G " liq mass flow rate, kg/s "

rho_G = 9.8241 " vap.density, kg/m^3"

mu_G = 6.0405 * 10^(-6) " vap viscosity, Pa-s"

epsilon = 0.0 "m ... roughness for smooth pipe"

**Now, apply the simple EES Procedure for two-phase pressure drop, using Haaland eqn, written above:**

CALL Lockhart_Martinelli_PrDrop(epsilon, D, rho_L, rho_G, mu_L, mu_G, m_L, m_G : G_L, G_G, Re_L, Re_G, f_L, f_G, dPdL_L, dPdL_G, X_tt, phi_L, phi_G, dPdL_tot1, dPdL_tot2)

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**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| $A$ = 0.03582 [$m^2$] | $D$ = 0.2136 [m] | $dPdL_G$ = 1.051 [Pa/m] | **$dPdL_L$ = 0.5437** [Pa/m] |
| $dPdL_{tot1}$ = 15.2027 [Pa/m] | **$dPdL_{tot2}$ = 15.2027** [Pa/m] | $\varepsilon$ = **0** [m] | $f_G$ = 0.01242 |
| $f_L$ = 0.01568 | $G_G$ = 18.84 [kg/s.$m^2$] | $G_L$ = 106.8 [kg/s.$m^2$] | $\mu_G$ = 0.000006041 [Pa-s] |
| $\mu_L$ = 0.0001211 [Pa-s] | $m_G$ = 0.675 [kg/s] | $m_L$ = 3.825 [kg/s] | $m_{tot}$ = 4.5 [kg/s] |
| $\phi_G$ = 3.803 | $\phi_L$ = **5.288** | $Re_G$ = 666225 | $Re_L$ = 188296 |
| $\rho_G$ = 9.824 [kg/$m^3$] | $\rho_L$ = 770.1 [kg/$m^3$] | x = 0.15 | $X_{tt}$ = **0.7192** |

---

**Thus, we see that two-phase pressure drop is 15.203 Pa/m.**
**Then, for 300 m long pipe, pressure drop is = 15.203 x 300 = 45.61 kPa .. Ans.**

"============================================================"

---

## PROB.V-B.33

**TWO-PHASE LIQUID OXYGEN FLOWS IN A 200-MM NOMINAL (8-IN. NOMINAL) SCHEDULE 10 PIPE AT A TOTAL MASS FLOW RATE OF 10 KG/S (79,400 lbm/hr) AND A QUALITY OF 0.200. THE LENGTH OF THE LINE IS 275 M (902 FT), AND THE FLUID TEMPERATURE IS 110 K. THE VAPOR DENSITY IS 19.40 KG/M3, AND THE LIQUID DENSITY IS 1035.4 KG/M3. DETERMINE THE TWO-PHASE FRICTIONAL PRESSURE DROP.[1]**

**Solution:**

**We will take properties of Oxygen at sat. temp of 110 K from NIST website:**

**Ref:** https://webbook.nist.gov/chemistry/fluid/

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# Liquid Phase Data

## Data on Saturation Curve

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) |
|---|---|---|---|---|---|---|---|
| 110.00 | 0.54340 | 1035.5 | 0.00096574 | -99.165 | -98.641 | 3.2855 | 0.86576 |

| Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Surf. Tension (N/m) | Phase |
|---|---|---|---|---|---|---|
| 1.8068 | 734.77 | -0.19639 | 122.72 | 0.12249 | 0.0083869 | liquid |

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# Vapor Phase Data

## Data on Saturation Curve

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) |
|---|---|---|---|---|---|---|---|
| 110.00 | 0.54340 | 21.281 | 0.046990 | 65.520 | 91.054 | 5.0100 | 0.69881 |

| Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Phase |
|---|---|---|---|---|---|
| 1.1014 | 188.14 | 17.250 | 9.0060 | 0.010795 | vapor |

**Now, let us write all data:**

D = 211.58E-03 "m.. ID of pipe for 200 mm nominal pipe, with OD = 219.1 mm, sch. 10, thickness = 3.76 mm"

A = pi * D^2 /4 "m^2 ... area of cross-section of pipe"

"Properties of sat. liq and vap oxygen from NIST website:"

rho_L = 1035.5 " liq.density, kg/m^3"

mu_L =122.72E-06 " liq viscosity, Pa-s"

m_tot = 10 "kg/s ... total flow rate"

x = 0.20 "..quality of flowing fluid"

m_G = m_tot * x "vap mass flow rate, kg/s "

m_L = m_tot - m_G " liq mass flow rate, kg/s "

rho_G = 21.281 " vap.density, kg/m^3"

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mu_G = 9.006E-06 " vap viscosity, Pa-s"

epsilon = 0.0 "m ... roughness for smooth pipe"

"Now, apply the simple EES Procedure for two-phase pressure drop, using Haaland eqn, written above:"

CALL Lockhart_Martinelli_PrDrop(epsilon, D, rho_L, rho_G, mu_L, mu_G, m_L, m_G : G_L, G_G, Re_L, Re_G, f_L, f_G, dPdL_L, dPdL_G, X_tt, phi_L, phi_G, dPdL_tot1, dPdL_tot2)

**We get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| $A$ = 0.03516 [$m^2$] | $D$ = 0.2116 [m] | $dPdL_G$ = 3.967 [Pa/m] | **$dPdL_L$ = 1.613** [Pa/m] |
| $dPdL_{tot1}$ = 51.1158 [Pa/m] | **$dPdL_{tot2}$ = 51.1158** [Pa/m] | $\varepsilon$ = **0** [m] | $f_G$ = 0.01104 |
| $f_L$ = 0.01365 | $G_G$ = 56.88 [$kg/s.m^2$] | $G_L$ = 227.5 [$kg/s.m^2$] | $\mu_G$ = 0.000009006 [Pa-s] |
| $\mu_L$ = 0.0001227 [Pa-s] | $m_G$ = 2 [kg/s] | $m_L$ = 8 [kg/s] | $m_{tot}$ = 10 [kg/s] |
| $\phi_G$ = 3.589 | $\phi_L$ = **5.629** | $Re_G$ = 1.336E+06 | $Re_L$ = 392293 |
| $\rho_G$ = 21.28 [$kg/m^3$] | $\rho_L$ = 1036 [$kg/m^3$] | x = 0.2 | $X_{tt}$ = **0.6376** |

**Thus, we see that two-phase pressure drop is 51.116 Pa/m.**

**Therefore, for a length of 275 m, the pressure drop is: 51.116 x 275 = 14.06 kPa .. Ans.**

"============================================================="

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## PROB.V-B.34

**DETERMINE THE COOL DOWN TIME AND LIQUID REQUIREMENT FOR A 100 MM NOMINAL, SCH. 5 INNER LINE TRANSFER LINE. LENGTH OF LINE IS 75 M, AND THE LINE CONTAINS 5 BAYONET JOINTS ( TOTAL MASS = 45 KG) AND ONE VALVE (MASS = 12 KG). THE LINE IS INITIALLY AT 300 K AND IS FILLED WITH NITROGEN GAS AT 101.3 KPA AND 300 K. LN2 AT 354.6 KPA IS USED TO COOL THE LINE TO A FINAL TEMPERATURE OF 89.8 K. AT STEADY STATE OPERATION, EXIT QUALITY IS 0.006 AND HEAT IN-LEAK FROM AMBIENT IS 6 W/M. THE ENTIRE LINE AND VALVE ARE CONSTRUCTED OF SS 304 HAVING A MEAN SPECIFIC HEAT OF 0.375 KJ/KG.K. THE VALVE AT THE END OF THE LINE HAS A FREE CROSS-SECTIONAL AREA OF 0.0018 M^2 AND A DISCHARGE COEFF. OF 0.6. [1]**

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**Solution:**

"Data:"

"100 mm nominal, sch. 5 pipe has OD - 114.3 mm, thickness = 2.1 mm, and ID = 110.1 mm"

D_o = 0.1143 "m"

D_i = 0.1101 "m"

t = 0.0021 "m"

A = 0.0018 "m^2 ... valve cross-sectional area at the end of the line"

L = 75 "m.... length of line"

rho = 7920 "kg/m^3 ... density of SS 304"

c_w_avg = 0.375 "J/kg.K.... avg sp. heat of metals"

T_o = 300 "K... initial temp of line"

T_ss = 89.8 "K... final steady state temp of line"

C_d = 0.6 "..discharge coeff of valve at the end of line"

gamma = 1.4 "sp. heat ratio for Nitrogen"

R = 296.8 "J/kg.K ... gas const for Nitrogen"

Q_ss = 6 * L * 10^(-3) "kW ... ext heat leak for L = 75 m, at the rate of 6 W/m... by data"

"Mass of inner line:"

m_w = pi * (D_o^2 -D_i^2) / 4 * L * rho "kg"

"Total mass to be cooled:"

Mw_tot = m_w + 45 + 12 "kg.... with 45 kg of 5 Bayonets, 12 kg of valve"

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"Total energy transferred from metal:"

Q_steel = Mw_tot * c_w_avg * (T_o - T_ss) "kJ"

"Total vol of inner line:"

V = pi * D_i^2 / 4 * L "m^3"

"Mean temp at exit:"

T_g2_avg = (T_o + T_ss) / 2 "K"

"Then, mean exit velocity:"

V2_sonic = C_d * (gamma * R * T_g2_avg )^(1/2) "m/s ... generally, exit is choked; so, this is sonic velocity at exit"

"Assuming that the liquid enters as sat. liq. ( x = 0), and exit quality = 0.006, we have: the mean quality = 0.003"

x_avg = 0.003

"At the exit pressure of 101.3 kPa and exit temp of 194.9 K, mean exit density, rho_g2_avg is**, from NIST website:i.e.** https://webbook.nist.gov/chemistry/fluid/ "

**Isobaric Data for P = 0.10130 MPa**

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) | Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Phase |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 194.90 | 0.10130 | 1.7554 | 0.56968 | 143.97 | 201.67 | 6.3923 | 0.74309 | 1.0438 | 284.37 | 4.8999 | 12.647 | 0.018259 | vapor |

rho_g2_avg = 1.7554 "kg/m^3 .. as shown above "

"And, again from NIST website, mean enthalpy at exit:"

h_g2_avg = 201.67 "kJ/kg …as shown above"

"And, mean gas flow rate at exit is:"

m_g2_avg = rho_g2_avg * A * V2_sonic "kg/s"

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"And, final fluid density, rho_ss is given by:"

rho_ss = 1 / ((1 - x_avg) / rho_f + x_avg / rho_g) "...gives final density, rho_ss, kg/m^3, rho_f = sat. liq. density, rho_g = sat. vap. density "

**"Get rho_f and rho_g from NISTwebsite:"**

**Liquid Phase Data**

**Data on Saturation Curve**

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) | Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Surf. Tension (N/m) | Phase |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 89.809 | 0.35460 | 746.01 | 0.0013405 | -96.404 | -95.928 | 3.1428 | 1.0205 | 2.1385 | 721.08 | -0.22808 | 103.16 | 0.12027 | 0.0061263 | liquid |

**Vapor Phase Data**

**Data on Saturation Curve**

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) | Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Phase |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 89.809 | 0.35460 | 14.846 | 0.067359 | 60.997 | 84.883 | 5.1561 | 0.80713 | 1.2624 | 181.72 | 20.896 | 6.4428 | 0.0089931 | vapor |

rho_f = 746.01 "kg/m^3 ... sat. liq. density at inlet at p = 354.6 kPa... from NIST website.. shown above"

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rho_g = 14.846 "kg/m^3 ... sat. vap. density at p = 354.6 kPa.... from NIST website … shown above"

h_f1 = -95.928 "kJ/kg ... enthalpy of liq at inlet, at 354.6 kPa and 89.8 K.... from NIST website….shown above"

u_f = -96.404 "kJ/kg ... internal energy of sat. liq at 354.6 kPa... from NIST website … shown above"

u_g = 60.997 "kJ/kg ... int energy of sat. vapor at 354.6 kPa... from NIST website…shown above"

"Therefore, avg int energy of fluid in steady state:"

u_ss = u_f + x_avg * (u_g - u_f) "kJ/kg"

"At initial condition of 101.3 kPa and 300 K, gas density, rho_go and int energy, u_o are, **from NIST website, shown below:**"

**Isobaric Data for P = 0.10130 MPa**

| Temperature (K) | Pressure (MPa) | Density (kg/m3) | Volume (m3/kg) | Internal Energy (kJ/kg) | Enthalpy (kJ/kg) | Entropy (J/g*K) | Cv (J/g*K) | Cp (J/g*K) | Sound Spd. (m/s) | Joule-Thomson (K/MPa) | Viscosity (uPa*s) | Therm. Cond. (W/m*K) | Phase |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 300.00 | 0.10130 | 1.1379 | 0.87882 | 222.17 | 311.19 | 6.8418 | 0.74317 | 1.0414 | 353.16 | 2.1196 | 17.897 | 0.025858 | vapor |

rho_go = 1.1379 "kg/m^3…shown above"

u_o = 222.17 "kJ/kg …. Shown above"

"Making these substitutions, cool down time is obtained as:"

cooldown_time =( Q_steel - V * ((rho_ss * (u_ss - h_f1) - rho_go * (u_o - h_f1))) ) / (m_g2_avg * (h_g2_avg - h_f1) - 0.5 * Q_ss)

**We get: cool-down time = 245.8 sec. = 4.1 min. .. see Results below:**

**Also:**

---

**"Liquid required to fill the line:"**

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m_f_fillline = V * (rho_ss -rho_go) "kg of liq."

**"Liquid required to take care of external heat leak:"**

m_f_heat_leak = (Q_ss * cooldown_time) / (2 * (h_g2_avg - h_f1)) " kg of liquid"

**"Liquid required to cool down the line:"**

m_f_cooldown = Q_steel / (h_g2_avg - h_f1) "kg of liquid"

**Results:**

**Unit Settings: SI K kPa kJ mass deg**

| | | | |
|---|---|---|---|
| $A = 0.0018$ [$m^2$] | $cooldown_{time} = 245.8$ [s] | $C_d = 0.6$ | $c_{w,avg} = 0.375$ [kJ/kg.K] |
| $D_i = 0.1101$ [m] | $D_o = 0.1143$ [m] | $\gamma = 1.4$ | $h_{f1} = -95.93$ [kJ/kg] |
| $h_{g2,avg} = 201.7$ [kJ/kg] | $L = 75$ [m] | $Mw_{tot} = 496.7$ [kg] | $m_{f,cooldown} = 131.6$ [kg] |
| $m_{f,fillline} = 463.3$ [kg] | $m_{f,heat,leak} = 0.1858$ [kg] | $m_{g2,avg} = 0.5395$ [kg/s] | $m_w = 439.7$ [kg] |
| $Q_{ss} = 0.45$ [kW] | $Q_{steel} = 39152$ [kJ] | $R = 296.8$ [J/kg.K] | $\rho = 7920$ [kg/$m^3$] |
| $\rho_f = 746$ [kg/$m^3$] | $\rho_g = 14.85$ [kg/$m^3$] | $\rho_{g2,avg} = 1.755$ [kg/$m^3$] | $\rho_{go} = 1.138$ [kg/$m^3$] |
| $\rho_{ss} = 650$ [kg/$m^3$] | $t = 0.0021$ [m] | $T_{g2,avg} = 194.9$ [K] | $T_o = 300$ [K] |
| $T_{ss} = 89.8$ [K] | $u_f = -96.4$ [kJ/kg] | $u_g = 61$ [kJ/kg] | $u_o = 222.2$ [kJ/kg] |
| $u_{ss} = -95.93$ [kJ/kg] | $V = 0.714$ [$m^3$] | $V2_{sonic} = 170.7$ [m/s] | $x_{avg} = 0.003$ |

**Thus:**

**Cool down time = 245.8 sec = 4.1 min … Ans.**

**Liquid required to cool down the line = m_f_cooldown = 131.6 kg … Ans.**

**Liquid required to fill the line = m_fillline = 463.3 kg … Ans.**

**Liquid required to take care of ext. heat leak = m_f_heatleak = 0.1858 kg … Ans.**

**Note:** From the Table given in Ref.[12], we know that amount of LN2 required (with cooling with the enthalpy of gas also included) is 0.33 litres/kg of SS 304. So, for 497 kg, we get: amount of LN2 required for cool down = 497 * 0.33 = 164.01 litres = 164.01 *

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0.8 kg = 131.21 kg. approx. ***This matches very well with the figure of 131.6 kg obtained with detailed calculations done above.***

---

**Prob. V B.34 is now solved using the built-in functions of EES to get fluid properties. See how convenient it is.**

```
"Prob.V-B.34 Determine the cool down time and liquid requirement for a 100 mm nominal, sch. 5 inner line transfer line. Length of line is 75 m, and the line contains 5 bayonet joints  ( total mass = 45 kg) and one valve (mass = 12 kg). The line is initially at 300 K and is filled with nitrogen gas at 101.3 kPa and 300 K. LN2 at 354.6 kPa is used to cool the line to a final temperature of 89.8 K. At steady state operation, exit quality is 0.006 and heat in-leak from ambient is 6 W/m. The entire line and valve are constructed of SS 304 having a mean specific heat of 0.375 kJ/kg.K. The valve at the end of the line has a free cross-sectional area of 0.0018 m^2 and a discharge coeff. of 0.6. [1]"

"Solution:"

"Data:"

"100 mm nominal, sch. 5 pipe has OD - 114.3 mm, thickness = 2.1 mm, and ID = 110.1 mm"

D_o = 0.1143 "m"

D_i = 0.1101 "m"

t = 0.0021 "m"

A = 0.0018  "m^2 ... valve cross-sectional area at the end of the line"

L = 75 "m.... length of line"

"Total mass to be cooled:"

Mw_tot =496.7  "kg.... with 45 kg of 5 Bayonets, 12 kg of valve"

c_w_avg = 0.375 "J/kg.K.... avg sp. heat of metals"

T_o = 300 "K... initial temp of line"

P_o = 101.3 "kPa ... initial pressure of gas in the line"

T_ss = 89.8  "K... final steady state temp of line"

C_d = 0.6  "..discharge coeff of valve at the end of line"

gamma = 1.4   "...sp. heat ratio for Nitrogen"
```

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```
R = 296.8   "J/kg.K ... gas const for Nitrogen"

Q_ss = 0.45  "kW ... ext heat leak for L = 75 m, at the rate of 6 W/m... by data"

Fluid$ = 'Nitrogen'

P_fluid = 354.6  "kPa ... pressure of sat. fluid entering the line"

{T_sat = 89.8 "K... sat. temp of fluid entering"}

"Assuming that the liquid enters as sat. liq. ( x = 0), and exit quality = 0.006, we have: the mean quality
= 0.003"

x_avg = 0.003

"-------------------------------------------------"

"Total energy transferred from metal:"

Q_steel = Mw_tot * c_w_avg * (T_o - T_ss)  "kJ"

"Total vol of inner line:"

V = pi * D_i^2 / 4 * L    "m^3"

"Mean temp at exit:"

T_g2_avg = (T_o + T_ss) / 2   "K"

"Then, mean exit velocity:"

V2_sonic = C_d * (gamma * R * T_g2_avg )^(1/2)  "m/s ... generally, exit is choked; so, this is sonic
velocity at exit"

"At the exit pressure of 101.3 kPa and exit temp of 194.9 K, mean exit density, rho_g2_avg is:  "

rho_g2_avg = Density(Fluid$,T=T_g2_avg,P= P_o)  "kg/m^3 ..from EES built-in  function"

"And, againmean enthalpy at exit:"

h_g2_avg = Enthalpy(Fluid$,T=T_g2_avg,P=P_o)    "kJ/kg ...from EES built-in function"

"And, mean gas flow rate at exit is:"

m_g2_avg = rho_g2_avg * A * V2_sonic   "kg/s"

"And, final fluid density, rho_ss is given by:"

 rho_ss=Density(Fluid$,x=x_avg,P=P_fluid)   "...gives final density, rho_ss, kg/m^3, from built-in
function of EES "

h_f1 = Enthalpy(Fluid$,x=0,P=P_fluid) "kJ/kg ... from built-in function of EES"

"Therefore, avg int energy of fluid in steady state:"

u_ss = IntEnergy(Fluid$,x=x_avg,P=P_fluid)  "kJ/kg.... from built-in function of EES"

"At initial condition of 101.3 kPa and 300 K, gas density, rho_go and int energy, u_o are:"

 rho_go = Density(Fluid$,T=T_o,P=P_o) "kg/m^3 ... from built-in function of EES"
```

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u_o = IntEnergy(Fluid$,T=T_o,P=P_o) "kJ/kg ... from built-in function of EES"

"Making these substitutions, cool down time is obtained as:"

cooldown_time =( Q_steel - V * ((rho_ss * (u_ss - h_f1) - rho_go * (u_o - h_f1))) ) / (m_g2_avg * (h_g2_avg - h_f1) - 0.5 * Q_ss) "sec."

"We get: cool-down time = 245.8 sec. = 4.1 min. .. see Results below:"

"Also:"

"Liquid required to fill the line:"

m_f_fillline = V * (rho_ss -rho_go) "kg of liq."

"Liquid required to take care of external heat leak:"

m_f_heat_leak = (Q_ss * cooldown_time) / (2 * (h_g2_avg - h_f1)) " kg of liquid"

"Liquid required to cool down the line:"

m_f_cooldown = Q_steel / (h_g2_avg - h_f1) "kg of liquid"

"Results:"

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $A = 0.0018$ [$m^2$] | $cooldown_{time} = 245.8$ [s] | $C_d = 0.6$ |
| $c_{w,avg} = 0.375$ [J/kg.K] | $D_i = 0.1101$ [m] | $D_o = 0.1143$ [m] |
| Fluid$ = 'Nitrogen' | $\gamma = 1.4$ | $h_{f1} = -95.93$ [kJ/kg] |
| $h_{g2,avg} = 201.7$ [kJ/kg] | $L = 75$ [m] | $Mw_{tot} = 496.7$ [kg] |
| $m_{f,cooldown} = 131.6$ [kg] | $m_{f,fillline} = 463.3$ [kg] | $m_{f,heat,leak} = 0.1858$ [kg] |
| $m_{g2,avg} = 0.5395$ [kg/s] | $P_{fluid} = 354.6$ [kPa] | $P_o = 101.3$ [kPa] |
| $Q_{ss} = 0.45$ [kW] | $Q_{steel} = 39152$ [kJ] | $R = 296.8$ [J/kg.K] |
| $\rho_{g2,avg} = 1.755$ [kg/$m^3$] | $\rho_{go} = 1.138$ [kg/$m^3$] | $\rho_{ss} = 650$ [kg/$m^3$] |
| $t = 0.0021$ [m] | $T_{g2,avg} = 194.9$ [K] | $T_o = 300$ [K] |
| $T_{ss} = 89.8$ [K] | $u_o = 222.2$ [kJ/kg] | $u_{ss} = -95.93$ [kJ/kg] |
| $V = 0.714$ [$m^3$] | $V2_{sonic} = 170.7$ [m/s] | $x_{avg} = 0.003$ |

**Note that the Results match with the results obtained earlier.**

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## PROB.V-B.35

**DETERMINE THE TIME REQUIRED TO COOL DOWN A 30 M (98.40-FT) SECTION OF 100-MM NOMINAL (4-IN. NOMINAL) STAINLESS STEEL TRANSFER LINE USED TO TRANSFER LIQUID HYDROGEN. THE MEAN SPECIFIC HEAT OF THE STAINLESS STEEL IS 315 J /KG-K, AND THE INNER LINE HAS A TOTAL MASS OF 180 KG (397 LB). THE INNER LINE IS INITIALLY AT 295 K (531°R) AND IS COOLED DOWN TO A FINAL TEMPERATURE OF 20.5 K (36.9°R). THE AVERAGE HEAT TRANSFER RATE FROM AMBIENT DURING THE COOLING PROCESS IS ($Q_{ss}$/2) = 70 W (239 BTU/HR). THE AVERAGE GAS ENTHALPY AT THE EXIT OF THE LINE IS 2270 KJ/KG, AND THE AVERAGE MASS FLOW RATE OF THE GAS FROM THE LINE DURING THE COOL-DOWN PROCESS IS 20 G/S. THE INTERNAL ENERGY OF THE GAS INITIALLY WITHIN THE LINE IS 2938 KJ/KG, AND THE DENSITY OF THE GAS INITIALLY WITHIN THE LINE IS 0.0832 KG/M3. THE DENSITY OF THE LIQUID FINALLY WITHIN THE LINE IS 70.51 KG/M3, AND THE FINAL INTERNAL ENERGY OF THE FLUID IN THE LINE IS 27L.7 KJ/KG. THE ENTHALPY OF THE LIQUID ENTERING THE LINE IS 273.2 KJ/KG. ALSO, DETERMINE THE MASS OF LIQUID REQUIRED TO FILL THE LINE AND TO COOL DOWN THE LINE.[1]**

**Solution:**

Here, most of the variables required to calculate cool down time and liquid requirements, are given.

**So, let us write a general EES Procedure to calculate the cool down time etc. when LN2 or LH2 are used:**

**Note:** Fluid 1 ---> “Nitrogen” Fluid 2 ---> “Hydrogen”

Gas constant R and avg. sp. heat of SS304 are different when LN2 or LH2 is used. This is taken care in the first two blocks of the program below.

Rest of the inputs and outputs are already defined in the problem above.

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PROCEDURE Cool_down_time_cryoline(Fluid$, Mw_tot, L, D, T_o, T_ss, Q_ext, h_g2_avg, m_g2_avg, u_o, rho_go, rho_ss, u_ss, h_f1 : Q_steel, & cooldown_time, mf_to_fillline, mf_towards_heatleak, mf_to_cooldown)

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{Determines the cool down time for the cryoline. Also gives the amount of liquid required :(a) to fill the line, (b) towards external heat in-leak, and (c) to cool down the line }

IF FLUID$ = 'Nitrogen' THEN

R = 296.8 "J/kg.K"

c_w_avg = 0.375 "kJ/kg.K"

ENDIF

IF FLUID$ = 'Hydrogen' THEN

R = 4124 "J/kg.K"

c_w_avg = 0.315 "kJ/kg.K"

ENDIF

Q_steel = Mw_tot * c_w_avg * (T_o - T_ss) "kJ"

V = pi * D^2 /4 * L "m^3 .... internal vol. of line"

cooldown_time =( Q_steel - V * ((rho_ss * (u_ss - h_f1) - rho_go * (u_o - h_f1))) ) / (m_g2_avg * (h_g2_avg - h_f1) - 0.5 * Q_ext)

mf_to_fillline = V * (rho_ss -rho_go) "kg of liq."

mf_towards_heatleak = (Q_ext * cooldown_time) / (2 * (h_g2_avg - h_f1)) " kg of liquid"

mf_to_cooldown = Q_steel / (h_g2_avg - h_f1) "kg of liquid"

END

"============================================================="

**Now, write the data for the problem given above:**

Fluid$ = 'Hydrogen'

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Mw_tot = 180 "kg"

L = 30 "m" ; D = 0.1101"m" ; T_o = 295 "K" ; T_ss = 20.5 "K" ; Q_ext = 0.14 "kW" ; h_g2_avg = 2270 "kJ/kg"

m_g2_avg = 0.02 "kg/s" ; u_o = 2938 "kJ/kg" ; rho_go = 0.0832 "kg/m^3" ; rho_ss = 70.51 "kg/m^3"

u_ss = 271.7 "kg/m^3" ; h_f1 = 273.2 "kJ/kg"

CALL Cool_down_time_cryoline(Fluid$, Mw_tot, L, D, T_o, T_ss, Q_ext, h_g2_avg, m_g2_avg, u_o, rho_go, rho_ss, u_ss, h_f1 : Q_steel, & cooldown_time, mf_to_fillline, mf_towards_heatleak, mf_to_cooldown)

"============================================================"

**And, applying the above EES Procedure, we get:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $cooldown_{time}$ = 392.758 [s] | D = 0.1101 [m] | Fluid$ = 'Hydrogen' |
| $h_{f1}$ = 273.2 [kJ/kg] | $h_{g2,avg}$ = 2270 [kJ/kg] | L = 30 [m] |
| $mf_{towards,heatleak}$ = 0.01377 [kg] | $mf_{to,cooldown}$ = 7.795 [kg] | $mf_{to,fillline}$ = 20.115 [kg] |
| $Mw_{tot}$ = 180 [kg] | $m_{g2,avg}$ = 0.02 [kg/s] | $Q_{ext}$ = 0.14 [kW] |
| **$Q_{steel}$ = 15564** [kJ] | $\rho_{go}$ = 0.0832 [kg/m$^3$] | $\rho_{ss}$ = 70.51 [kg/m$^3$] |
| $T_o$ = 295 [K] | $T_{ss}$ = 20.5 [K] | $u_o$ = 2938 [kJ/kg] |
| $u_{ss}$ = 271.7 [kJ/kg] | | |

**Thus:**

**Cool down time = 392.76 sec = 6.55 min…. Ans.**

**Mass of liquid required to fill the line = 20.12 kg…Ans.**

**Mass of liquid required to cool down the line = 7.795 kg … Ans.**

"============================================================"

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## PROB.V-B.36

### SOLVE PROB.V-B.34 USING THE ABOVE EES PROCEDURE:

**We have the data:**

Fluid$ = 'Nitrogen'

Mw_tot = 496.7 "kg"

L = 75 "m" ; D = 0.1101"m" ; T_o = 300 "K" ; T_ss = 89.8 "K" ; Q_ext = 0.45 "kW" ; h_g2_avg = 201.67 "kJ/kg"

m_g2_avg = 0.53951 "kg/s" ; u_o = 222.17 "kJ/kg" ; rho_go = 1.1379 "kg/m^3" ; rho_ss = 650 "kg/m^3"

u_ss = -95.93 "kg/m^3" ; h_f1 = -95.93 "kJ/kg"

CALL Cool_down_time_cryoline(Fluid$, Mw_tot, L, D, T_o, T_ss, Q_ext, h_g2_avg, m_g2_avg, u_o, rho_go, rho_ss, u_ss, h_f1 : Q_steel, &

cooldown_time, mf_to_fillline, mf_towards_heatleak, mf_to_cooldown)

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**We get from the EES Procedure:**

**Unit Settings: SI K kPa kJ mass deg**

| | | |
|---|---|---|
| $cooldown_{time}$ = 245.806 [s] | D = 0.1101 [m] | Fluid$ = 'Nitrogen' |
| $h_{f1}$ = -95.93 [kJ/kg] | $h_{g2,avg}$ = 201.7 [kJ/kg] | L = 75 [m] |
| $mf_{towards,heatleak}$ = 0.1858 [kg] | $mf_{to,cooldown}$ = 131.6 [kg] | $mf_{to,fillline}$ = 463.317 [kg] |
| $Mw_{tot}$ = 496.7 [kg] | $m_{g2,avg}$ = 0.5395 [kg/s] | $Q_{ext}$ = 0.45 [kW] |
| $Q_{steel}$ = **39152** [kJ] | $\rho_{go}$ = 1.138 [kg/m$^3$] | $\rho_{ss}$ = 650 [kg/m$^3$] |
| $T_o$ = 300 [K] | $T_{ss}$ = 89.8 [K] | $u_o$ = 222.2 [kJ/kg] |
| $u_{ss}$ = -95.93 [kJ/kg] | | |

**Thus:**

**Cool down time = 245.81sec = 4.1 min…. Ans.**

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**Mass of liquid required to fill the line = 463.317 kg…Ans.**

**Mass of liquid required to cool down the line = 131.6 kg … Ans.**

**Note: These answers are the same as obtained for Prob.V-B.34**

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